Powering Paralympians

The Fundamentals of Nutritional Guidelines for Paralympic Athletes

Vera Catharina Ruth Weijer

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TABLE OF CONTENTS

Chapter 1	General introduction	7
Chapter 2	Energy requirements of Paralympic athletes: insights from the doubly labeled water approach	33
Chapter 3	Measured and predicted resting metabolic rate of Dutch and Norwegian Paralympic athletes	63
Chapter 4	Feasibility and accuracy of body fat assessment using standardized skinfold thickness assessment versus dual-energy x-ray absorptiometry in Paralympic athletes	87
Chapter 5	Do Paralympic athletes suffer from brittle bones? Prevalence and risk factors of low bone mineral density in Paralympic athletes	113
Chapter 6	Continuous glucose monitoring in Para cyclists: An observational study	139
Chapter 7	General discussion	163
Addenda	Summary	201
	Samenvatting	206
	Impact	209
	Dankwoord	213

Chapter 1

General introduction

Growing Parasport

The Para-sport community is experiencing significant growth. In the Netherlands alone 1.7 million individuals live with a moderate to severe physical disability (1). Physical activity holds paramount importance for individuals with disabilities, offering benefits such as improved psychological wellbeing, higher quality of life, and lower risk of many chronic diseases (2, 3). The increasing prominence of Paralympic sport is exemplified by the significant increase in participation, from 400 athletes at the first Paralympic games in Rome in 1960 to 4400 athletes at the Paris 2024 Paralympic games (4). According to the international Paralympic committee (IPC) any athlete who is competing or has competed in the Paralympic games is considered a Paralympic athlete, whereas a Para athlete is any athlete competing in sports whilst having a disability. The increased popularity in Paralympic sports necessitates professional guidance for the athletes. Coaches, physiotherapists, sport physicians and dieticians collaborate to improve the performance of the athlete, while maintaining good mental and physical health. Nutrition has a major impact on physical health and performance, making evidence-based nutritional guidance essential for athletes. Sport dieticians and nutritionists are tasked with guiding athletes towards optimal dietary practices. However, the current education and training of these nutrition professionals, as well as current nutritional guidelines, are predominantly focused on athletes without disabilities. Specific knowledge regarding the nutritional needs of Paralympic or Para athletes remains limited, largely due to the scarcity of research in this area. Addressing this knowledge gap and educating sport dieticians and nutritionists on the unique nutritional requirements of Paralympic athletes is crucial to adequately support this growing athletic population.

Nutrition guidelines for Para-athletes

Although many nutritional guidelines are available for regular athletes (5-7) they cannot simply be applied to Para athletes. For instance, the body composition can differ from athletes without a disability (8), directly influencing the energy requirements of Para athletes (9) and, as such, also their nutritional needs. Furthermore, carbohydrate and protein intake recommendations are commonly based on body mass (5), which might not apply when the body composition is changed due to a disability. The nutritional guidelines that do exist for Para athletes are often derived from those for regular athletes and are often insufficiently tailored to the unique needs of Para athletes (10). Moreover, much of the existing research either focuses on a single type of disability, with most

attention going towards spinal cord injury (SCI) (11), or on a single type of exercise (12, 13), which limits the broader applicability of findings. These significant gaps underline the urgent need for more targeted, evidence-based research to develop comprehensive nutritional strategies that cater to the diversity of Paralympic athletes, ensuring that fundamental sports nutrition principles are effectively adapted to their unique nutritional needs.

Basic principles of sport nutrition

To develop effective nutritional strategies for Para athletes, it is crucial to first understand the aim and fundamental principles of sports nutrition. The main aim of nutritional counseling is to optimize performance on the day of competition while also maximizing training adaptations, recovery, and overall health to ensure optimal performance (10). One key principle of sport nutrition is ensuring adequate energy intake to fuel the energetic demands of training and competition, maintain the body's basal physiological functions (14), and support body composition management, which is important for improving strength, power, and endurance, depending on the specific demands of the sport (15). Macronutrient distribution is also crucial, with carbohydrate intake as the primary fuel for high-intensity exercise (5), protein to condition musculoskeletal tissues, and fats for energy, hormonal function, and vitamin absorption (16). Nutritional periodization aligns intake with the training schedule to enhance adaptations and further improve performance (17). Besides the macronutrients, the micronutrients, which play a crucial role in various physiological functions, must be obtained through the diet, as they cannot always be synthesized endogenously (18). Along with food intake, sufficient fluid intake should also be encouraged, since dehydration is detrimental for performance (19). One last nutritional principle is reducing the risk of injury and illness, to minimize training interruptions, thereby supporting consistent performance improvements. Collectively, these principles aim to support optimal performance, health, and facilitate recovery. This thesis will focus on the energy requirements and body composition of Para athletes, as these factors underpin many aspects of nutritional guidance.

Energy requirements

Proper energy intake is recognized as the corner stone of an athlete's diet (6). When in energy balance, the energy expenditure determines the energy requirements of the athlete. Ensuring adequate energy intake ensures optimal training intensity, effective recovery, and prevent fatigue and overtraining (6). Additionally, understanding an athlete's energy expenditure can aid in manipulating body weight and body composition by adjusting energy intake accordingly. Knowledge about the energy expenditure allows for targeted dietary strategies to achieve better performance, health and body composition goals.

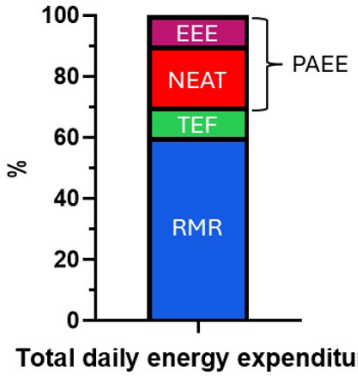

Figure 1.1. The components of total energy expenditure with their contributions in percentages, for an average person. The contribution of the components varies among individuals and fluctuates daily. RMR = resting metabolic rate; TEF = thermic effect of food; NEAT = Non-exercise activity energy expenditure; EEE = exercise energy expenditure; PAEE = Physical activity energy expenditure.

TDEE

The total daily energy expenditure (TDEE) reflects the sum of all energy used by the body throughout the day. It is composed of the resting metabolic rate (RMR), thermic effect of food (TEF) and the physical activity energy expenditure (PAEE) (Figure 1.1). In sedentary individuals, RMR accounts for about 60-80% of the TDEE (20), while the TEF accounts for roughly 10%, with the remainder attributed to PAEE. However, these proportions differ in athletes due to elevated levels of physical activity. In elite athletes, PAEE typically comprises 40-50% of TDEE (21), with extreme cases reporting PAEE contributions as high as 80% of TDEE (22, 23). There are several methods to assess the TDEE (24). An accurate laboratory-based method is the respiratory chamber, where participants are confined to a sealed environment for an extended period of time.

Within the chamber, carbon dioxide production and oxygen consumption are measured and subsequently converted into energy expenditure (25). However, this method restricts participant mobility and may not reflect daily life energy expenditure. An accurate alternative technique to assess daily energy expenditure under free-living conditions is the doubly labeled water method. This method involves administering a known volume of stable isotopes of hydrogen (^{2}H) and oxygen (^{18}O) in the form of water. After the labeled water is allowed to distribute throughout the body, changes in isotope levels are then monitored for the next 8–14 days from urine samples. Over the measurement period, the concentrations of both isotopes decline because of loss of hydrogen (^{2}H) isotopes and oxygen (^{18}O) isotopes through water (H_2O) and carbon dioxide (CO_2) through respiration. The differential elimination rates of these isotopes from the body are used to calculate CO_2 production, which serves as an indicator of energy expenditure over time (26). While this method provides accurate data in a free living situation, it is costly and requires specialized equipment and personnel. Therefore, in practice the TDEE is usually estimated instead of measured. Sport nutritionists or dieticians typically begin by measuring or estimating the RMR. Subsequently, energy allowances are applied by either multiplying the RMR by a physical activity level factor or by adding estimated energy expenditures from individual activities.

RMR

The RMR is the energy required to maintain physiological functions such as breathing, blood circulation, thermoregulation, and immune function. RMR is influenced by a range of biological and environmental factors, with body size being the most significant factor (27). Among the components of body mass, FFM exerts the greatest influence, accounting for approximately 63% of the inter-individual variability in RMR (28, 29). This influence can be attributed to the high metabolic activity of FFM, even in rest (27). RMR tends to decline with age, due to both changes in body composition and metabolic efficiency (27). Additionally, hormones such as triiodothyronine (30) or chronic illnesses, infections or fevers (31) can lead to increases in RMR due to heightened metabolic demands. Environmental factors also contribute to variations in RMR. For example, exposure to cold temperatures (32) and the consumption of stimulants like caffeine have shown to elevate the RMR (33).

For determining the resting metabolic rate, several methods exist. Similar to the measurement of the TDEE, a respiratory chamber can be used. However, a more practical method is the ventilated hood method. In this

approach, the participant lies down while a hood is placed over their head to measure the CO_2 and O_2 exchange. The application of this method usually takes about 30 minutes and requires strict conditions for an accurate measurement (34). Those conditions include: a minimum of 5 hours of fasting; no nicotine 2 hours before and no caffeine 4 hours before the measurement; a rest period of 10 to 20 minutes before the measurement; no moderate to anaerobic exercise 2h before the measurement and no vigorous exercise 14 hours before the measurement; a room temperature of 20-25 degrees Celsius during the measurement (34). For measuring the basal metabolic rate the conditions are stricter, with a fasting period of at least 10-12 hours and measuring directly after 8h of sleep to prevent any physical activity before the measurement (35, 36). Because of the strict conditions for basal metabolic rate measurements, many researchers measure RMR instead (5). While indirect calorimetry is an accurate method, it is also time invasive and requires specialized equipment. Therefore, in practice, dieticians estimate RMR by common prediction equations. Since body mass or FFM are considered the most important predictors of RMR, prediction equations estimating the RMR commonly use either body mass or FFM as main predictor, often complemented with factors such as height, age, sex, and/or fat mass (37, 38).

TEF

The TEF is the energy used for digestion and absorption of nutrition. The TEF can be measured by assessing the energy expenditure after food ingestion, in for example a respiratory chamber, and subtracting the previously measured RMR from the total energy expenditure, while the participant is inactive. However, this method is complex and limits the freedom of the participant. Therefore, in practice it is commonly estimated to be about 5-15% of the TDEE (39).

PAEE

The physical activity energy expenditure can be divided into the exercise energy expenditure, which is the energy needed for planned sport activities, and the non-exercise activity thermogenesis, which includes the energy needed for daily tasks such as walking or household tasks. Physical activity energy expenditure is the most fluctuating part of the total daily energy expenditure, especially among athletes (21). The exercise energy expenditure of athletes changes throughout the year, based on the phase of training (preparation phase or competition phase) and the volume of exercise corresponding to the phases (40).

To determine the TDEE the PAEE needs to be either measured or estimated. The PAEE can be assessed with indirect calorimetry in a respiration chamber, which provides accurate data but limits the daily physical activity due to the confined space. Alternatively, indirect calorimetry can also be used to measure the energy expenditure during specific activities, by having the participant wear a mask. Though these measurement may provide quality data, this method is invasive and cannot be applied for long periods of time. PAEE can also be estimated by wearing an accelerometer, that tracks the quantity and intensity of physical activity throughout the day (41). The devices use algorithms to convert these data into energy expenditure estimates. However, these algorithms may be less accurate for certain populations, such as the elderly, children, or individuals with disabilities (42). In practice the PAEE is commonly estimated. Energy expenditure for many sporting and daily activities has been determined via indirect calorimetry and compiled into compendia for the general population (43) and for wheelchair users (44). Dieticians use these compendia to estimate the energy expenditure for various activities, expressed as the metabolic equivalent of task (MET).

Energy availability

When the energy intake is chronically lower than the energy expenditure, it may lead to the so-called state of low energy availability. Energy availability is defined as the amount of energy available to the body for all physiological functions after accounting for the energy expended during exercise (6) and reflects the difference in energy intake and exercise energy expenditure in relation to fat-free mass (FFM) (Equation 1) (45). The cut off values for low energy availability are listed in Table 1.1, but in general energy availability > 45 kcal/kg FFM for women and > 40 kcal/kg FFM for men are considered optimal for physiological functions (46). When an athlete is exposed to low energy availability for a longer period of time, it can lead to various symptoms including high injury rates, low bone mineral density, and menstrual dysfunction in women (47). When these symptoms co-occur with low energy availability, this state is commonly referred to as 'relative energy deficiency in sports' (REDs) (47). Due to the severe consequences on both health and performance it is important to prevent chronic low energy availability and support athletes in achieving energy intake targets for optimal health and performance.

Table 1.1. The equation to calculate the energy availability and the cut off values separated for males and females.

Equation 1		
Energy availability = (energy intake – exercise energy expenditure) / fat free mass		
Cut off values		
	Male	Female
High EA	> 40 kcal/kg FFM	> 45 kcal/kg FFM
Optimal EA	≥ 40 kcal/Kg FFM	≥ 45 kcal/kg FFM
Subclinical LEA	30-40 kcal/kg FFM	30-45 kcal/kg FFM
Clinical LEA	<30 kcal/kg FFM	<30 kcal/kg FFM

EA = energy availability; LEA = low energy availability; FFM = fat free mass. Table adapted from Melin et al. (46)

Body composition

Body composition refers to the proportion of fat mass and FFM, including muscle, bone, organs, and water in the body. Since FFM is highly metabolic active it is closely related to the RMR and TDEE (27) and variations in body composition can significantly influence the energy needs of athletes. Some athletes strive for a low body mass to gain advantages in their sport. Low body mass can benefit athletes in gravitational sports like road cycling for mechanical efficiency, in weight-class sports like lightweight rowing by allowing competition in lower weight categories, and in aesthetic sports like gymnastics (15). Many athletes try to achieve a low body fat percentage to optimally use those advantages. However, adipose tissue plays a vital role in various endocrine processes, such as hormone production. A strong decline in body fat mass could lead to low testosterone levels in men and low estradiol levels in women (48). Therefore, the balance between the biomechanical advantage versus a healthy body composition is delicate and should be treated as such. For dieticians it is important to keep track of the body composition to guide athletes to achieving the optimal body composition for the individual athlete. Currently, various methods exist to measure the body composition of athletes, some are laboratory based and some are field measurements (49). Laboratory techniques mainly use imaging equipment to assess body composition, such as magnetic resonance imaging or dual energy X-ray absorptiometry (DXA). DXA scans were developed for the assessment of bone mineral content but also measure fat mass and FFM. Although this technique is precise in the measurement of FFM in athletes (50, 51), it is also expensive and not always practical to use. For field measurements bioimpedance can be used. Bioimpedance measures tissue resistance to

an electrical current to estimate body composition. FFM is conductive, while fat mass presents higher impedance. The method is, however, very sensitive to hydration status. Another field method, which is commonly used by dieticians are skinfold measurements. The measurements are simple and quick and the calipers are inexpensive and portable (49). The dietician measures 4 to 8 standardized skinfolds to assess subcutaneous fat mass and extrapolates this to whole body fat mass. Keeping track of changes in body composition over time is important, because it can have an impact on performance, health, and on nutritional needs (15). However, as the skinfold measurements are not yet validated to assess body fat mass for athletes with disabilities, it remains unclear if this practical measurement can be used for tracking changes in the body composition of Para athletes.

Common disabilities: pathophysiology and symptoms

To gain a better understanding of the nutritional needs of Para athletes, the various symptoms and physiological aspects of common disabilities need to be understood, since these may impact the nutritional requirements of the individual athlete. The IPC considers ten eligible impairments (52), often divided over three groups a) physical impairments, comprising the eight impairments that cause activity limitations that are biomechanical in nature – impaired muscle power, impaired range of movement, limb deficiency, leg length difference, hypertonia, ataxia, athetosis, and short stature; b) visual impairment and c) intellectual impairment (53). However, classification systems vary across sports, based on the proposed impact of the impairment on performance. For example, in wheelchair tennis, athletes with impaired muscle power in the legs due to SCI may compete against an athlete with a leg amputation, whereas athletes with an additional upper body impairment will compete in a separate category. This is due to the fact that the upper body impairment has an extra influence on the performance in wheelchair tennis. This highlights the importance to categorize athletes based on the impact the impairment may have on the outcome, in this case sport performance. A similar approach is relevant in nutritional counseling, as certain impairments may lead to similar physiological effects and, consequently, similar nutritional requirements. For example, a birth defect on one leg, can have similar physiological effects on nutritional requirements as an amputation of the leg at a later age. Conversely, other disabilities may result in unique physiological changes necessitating tailored nutritional strategies, for example missing a leg is not the same as a SCI. For this thesis, five distinct categories of impairments were considered, based on

their anticipated prevalence amongst Paralympic athletes and the physiological impact they may have on nutritional needs.

Spinal cord disorders

Physiology

The first condition is a spinal cord disorder (SCD), which includes all disabilities with damage to the spinal cord, e.g. traumatic and non-traumatic SCI and spina bifida. While spina bifida is congenital, SCI is typically acquired later in life due to a traumatic accident or disease affecting the spine. These conditions disrupt communication between the brain and the rest of the body and vice versa, resulting in varying degrees of loss in motor functions, sensory functions, and in some cases autonomic dysregulation (54). Most literature focuses on SCI, while research on spina bifida remains limited. However, the physiological consequences of both are likely comparable. The extent of the impairment largely depends on the level of SCI, affecting all innervation below the lesion. The spinal cord is divided into 31 segments, 8 cervical, 12 thoracal, 5 lumbar, 5 sacral and 1 coccygeal. Each segment communicates with a different part of the body (55). For example, the thoracal nerves control the trunk, while the lumbar nerves control the legs. Higher-level spinal cord disorders affect more segments, leading to greater loss of communication between the brain and the body (56). Athletes with spinal cord disorders often experience denervation of the leg muscles, as these are innervated by lower spinal cord segments. This commonly results in muscle atrophy, reduced FFM, and reliance on wheelchairs. Wheelchair dependency increases the risk for pressure ulcers. Besides the somatic motor dysfunction, spinal cord disorders can also impair autonomic nervous system functions (54). The autonomic nervous system, responsible for regulating involuntary processes such as heart rate, respiration, and digestion (57), consists of the parasympathetic (rest-and-digest) nervous system, which slows the heart rate, promotes digestion, and conserves energy, and the sympathetic (fight-or-flight) nervous system, which increases heart rate, dilates airways, and redirects blood flow to muscles to prepare the body for stress or danger. The parasympathetic nervous system is mostly activated from nerves leaving the spinal cord from the brain stem with some activation from the sacral nerves, whereas the sympathetic nervous system is activated from nerves leaving the spinal cord at the thoracal and lumbar segments (Figure 1.2) (58). Furthermore, the sympathetic nervous system also stimulates the adrenal glands from the lumbar region, which in turn produce noradrenalin and further

stimulate the sympathetic nervous system. Since the parasympathetic nervous system is mostly activated from the high spinal nerves, while the sympathetic nervous system mostly from the lower nerves, problems with the sympathetic nervous system arise in athletes with spinal cord disorders. This has multiple consequences on various organ systems including cardiovascular function, respiration, gastrointestinal function, micturition, sexual function, sudomotor activity, and thermoregulation (58). The reduction of sympathetic nervous system activity also affects the (resting) metabolic rate, partly due to a decrease in thermogenesis (59). The dysregulation of the autonomic nervous system can even lead to autonomic dysreflexia. This is generally defined as a syndrome that incorporates a sudden, exaggerated reflexive increase in blood pressure in response to a stimulus, usually bladder or bowel distension, originating below the level of the neurological injury and can be lethal if not counteracted in time (60).

Impact on nutritional needs

The physiological changes associated with spinal cord disorders can substantially influence nutritional needs. One key impact is on the energy requirements. As FFM is the main determinant of energy expenditure, a reduction in FFM due to muscle atrophy, caused by denervation of the muscles will likely lead to a decrease in both RMR as well as total energy expenditure. Studies have reported that individuals with SCI exhibit a 10–27% lower RMR compared to individuals without a disability (61–65). However, when the RMR is adjusted for reductions in FFM, the disparity decreases to 2–3% (64, 65). Although FFM appears to be the primary determinant of RMR even in individuals with SCI, this relationship is not linear, as individuals with high lesions and low FFM tend to have lower than expected RMR relative to their FFM (66, 67). Monroe *et al.* (62) suggested that lower sympathetic nervous system activity in individuals with SCI may contribute to further reductions in RMR, independent of changes in FFM. Moreover, this reduction in sympathetic nervous system activity can also lower the energy expenditure during exercise. Due to the reduction in sympathetic nervous system activity, athletes with SCI do not achieve the same absolute exercise intensities during training and competition when compared to control subjects without a disability, which is reflected by lower peak heart rates and peak oxygen uptake during exercise (68, 69). The potential reduction in exercise energy expenditure leads to a lower physical activity energy expenditure and thus TDEE, if the non-exercise activity thermogenesis stays equal. The physical activity energy expenditure can also be affected by wheelchair use, as many

individuals with SCI are wheelchair bound. Wheelchair users mainly rely on the upper body for propulsion and movement, which involves less and smaller muscle(groups) compared to walking and using the legs, which in turn reduces the energy expenditure. For example, wheelchair use is typically associated with lower energy cost of daily activities, such as dusting, grocery shopping or vacuuming (44, 61). Moreover, the exercise energy expenditure of athletes performing exercise in a wheelchair may be lower compared with the equivalent sport without the use of a wheelchair. This is for example reflected in the difference in MET values between wheelchair basketball for individuals with SCI (6.6 MET) (61) and regular basketball (7.5 MET) (70). Additionally, measuring PAEE of wheelchair athletes with an accelerometer can be challenging. To obtain more accurate data, it is often better to mount the accelerometer to the wheelchair rather than the athlete themselves (71). Besides the energy expenditure, wheelchair usage may also impact bone mineral density. In theory, athletes who mostly use wheelchairs have less weightbearing on the lower body and, therefore, a higher risk of low bone mineral density. Low BMD may predispose athletes to (stress)fractures as well as early osteoporosis (72). Frequent wheelchair use may also lead to pressure ulcers, which may increase the need for more protein in the diet to aid in wound healing (73, 74). Furthermore, athletes with SCI can have trouble with proper hydration, due to the risk of autonomic dysreflexia by bladder distention, which can lead to athletes being hesitant to take in large quantities of fluid. Also the limited access to wheelchair accessible bathrooms can lead to lower fluid intakes. Additionally, sweat rates can be decreased below the level of lesion, which can also affect fluid requirements and thermoregulation (75). Finally, SCI can also lead to slower gastric emptying and constipation (76), which in turn can trigger autonomic dysreflexia (60). Therefore, individuals with SCI can be hesitant with regards to the intake of fibers, since a high fiber consumption without commensurate fluid intake can lead to constipation with an already decreased bowel motility (11).

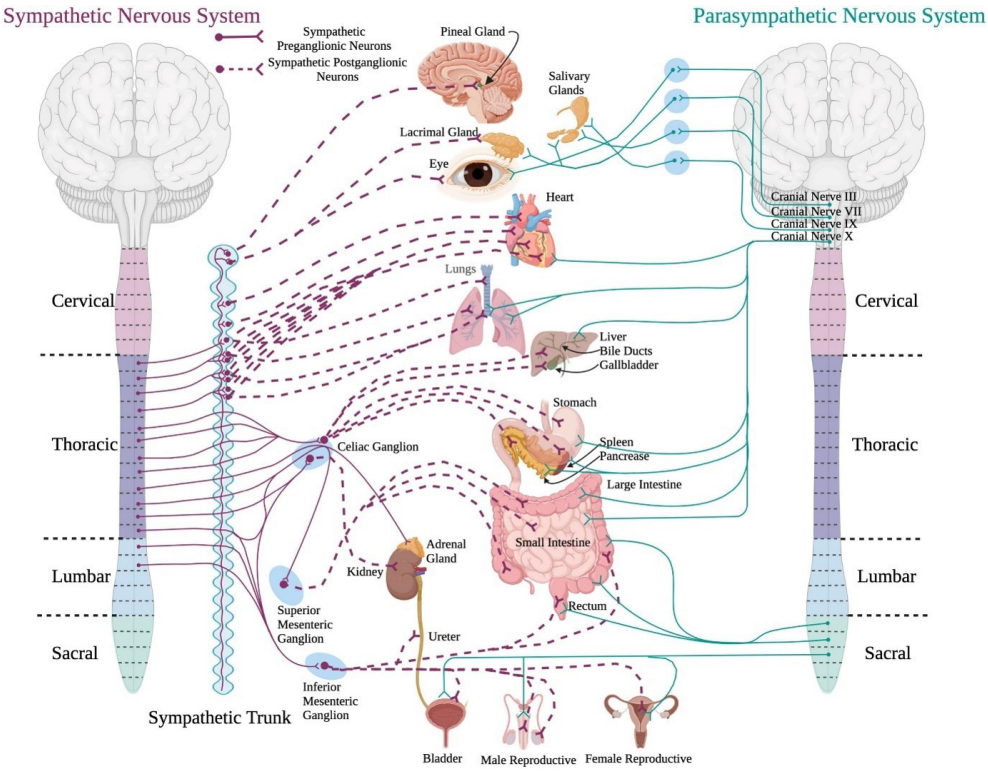

Figure 1.2. Schematic overview of the sympathetic and parasympathetic nervous systems (58).

Neurological disorders

Physiology

Another condition that can alter nutritional needs are neurological conditions, involving brain damage, including cerebral palsy (CP). CP is a result of brain damage within the first two years of life and can occur during the prenatal, perinatal, or postnatal periods, with 92% occurring in the pre or perinatal period (77). CP is defined as: "a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to nonprogressive disturbances that occurred in the developing fetal or infant brain" (78). In other words, because of damage in the developing brain before, during, or short after birth, the individual experiences difficulties in movement and posture, which lead to limitations in physical activity. The motor disorders of CP are often accompanied by disturbances of sensation, perception, cognition, communication, and behavior; by epilepsy, and by secondary musculoskeletal problems (78). The symptoms of these disabilities vary widely between

individuals, but the motor disorders mainly include hemiplegia (paralysis on one side of the body), hypertonia (increased muscle tension), ataxia (uncoordinated movements) and athetosis (continuous slow involuntary movements). Consequently, there is a large range in functionality between athletes with CP. The Cerebral Palsy International Sports and Recreation Association (CPISRA) and the IPC came up with a classification system, divided into eight classes with class 1 to 4 being wheelchair dependent and class 5 to 8 ambulatory. Based on this system athletes are classified into their sports category. However, within scientific literature this classification system is not often used and the gross motor function classification system (GMFCS) is more often employed to evaluate the level of disability during childhood. This system is highly predictive of adult motor function (79). The GMFCS categorizes individuals into five levels, ranging from level one, where the child can walk independently, to level five, where a motorized wheelchair is required for mobility (Table 1.2). Although this classification system is less commonly used in adults, the differences in functionality are roughly the same.

Impact on nutritional needs

Neurological disorders can significantly impact the nutritional needs of athletes. Energy requirements, in particular, may be either higher or lower compared to athletes without a disability, depending on the severity of the disorder and functional capacity. In children, the energy expenditure for ambulation is closely associated with the GMFCS (80), with the energy cost for walking going up with each level, due to an adapted gait with or without the use of mobility aids (81). However, the extra energy cost for ambulation could lead to lower physical activity levels in individuals with CP. Indeed, individuals with level I to III on the GMFCS spent 76-85% of the time sedentary (82), which leads to a low(er) physical activity level and PAEE. This was, however, measured in non-athletes with CP, in whom the sedentary time is likely greater when compared to athletes with CP. Furthermore, individuals using a (motorized) wheelchair, are likely to have a reduced energy expenditure for daily activities (44). In contrast, hypertonia and athetosis may increase resting energy expenditure due to the constant muscle tension and involuntary movements (83-85). Wheelchair use also leads to an additional risk for low bone mineral density in the lower body. Furthermore, the more severe cases of neurological disorders can lead to cognitive impairments or dysphagia (difficulty swallowing). Cognitive impairments can hinder an individual's ability to understand or manage their nutritional needs. Dysphagia, on the other hand, often necessitates dietary modifications,

such as consuming less solid foods, or additional tube feeding (86), these adaptations may result in insufficient caloric intake (87).

Table 1.2. The gross motor function classification system for children with cerebral palsy in the age 6–12 years (103).

Level I	Children walk indoors and outdoors, and climb stairs without limitations. Children perform gross motor skills including running and jumping but speed, balance, and coordination are reduced.
Level II	Children walk indoors and outdoors, and climb stairs holding onto a railing but experience limitations walking on uneven surfaces and inclines, and walking in crowds or confined spaces. Children have at best only minimal ability to perform gross motor skills such as running and jumping.
Level III	Children walk indoors or outdoors on a level surface with an assistive mobility device. Children may climb stairs holding onto a railing. Depending on upper limb function, children propel a wheelchair manually or are transported when travelling for long distances or outdoors on uneven terrain.
Level IV	Children may maintain levels of function achieved before age 6 or rely more on wheeled mobility at home, school, and in the community. Children may achieve self-mobility using a power wheelchair.
Level V	Physical impairments restrict voluntary control of movement and the ability to maintain antigravity head and trunk postures. All areas of motor function are limited. Functional limitations in sitting and standing are not fully compensated for through the use of adaptive equipment and assistive technology. At level V, children have no means of independent mobility and are transported. Some children achieve self-mobility using a power wheelchair with extensive adaptations.

Limb deficiencies

Physiology

Limb deficiencies refer to conditions where one or more limbs (arms or legs) are partially or entirely absent, underdeveloped, or malformed. These deficiencies can be congenital, i.e. dysmelia or non-congenital i.e. amputations. Dysmelia is defined as either hypoplasia (underdevelopment) or aplasia (complete absence) of one or more (parts of) limbs (88). The condition can also be divided in longitudinal or transverse limb deficiencies. Longitudinal deficiencies involve aplasia or hypoplasia of a bone along the long axis of the limb, eg, radial aplasia (88). For congenital limb deficiencies, upper limb deficiencies have a 2 to 3 fold higher incidence rate compared to lower limb deficiencies (89). For amputations, transverse deficiencies are most common, which involves (part of) a limb missing below a specific point along its length (88). Amputations in the lower body are categorized as partial foot, ankle disarticulation, transtibial, knee disarticulation, transfemoral, hip disarticulation, or

transpelvic, depending on the level of amputation. Similarly for the upper body, it can be categorized as partial hand, wrist disarticulation, transradial, elbow disarticulation, transhumeral, shoulder disarticulation or scapulathoracic disarticulation (90). The absence of one or more limbs is associated with a lower absolute FFM compared with individuals without a disability. Furthermore, limb deficiencies can cause a difference in locomotion. Athletes can make use of protheses, crutches, and or wheelchairs for locomotion and during exercise.

Impact on nutritional needs

The absolute lower FFM with limb deficiencies is associated with a lower absolute RMR. However, FFM consists of organs, muscles, and bones. As the FFM of limbs mainly include muscles and bone, the ratio between organ and muscle mass may slightly change. Organs such as brain, liver, kidneys and heart, use more energy at rest when compared to musculoskeletal tissues (91). Therefore, prediction equations of RMR based on individuals without a disability, which include body mass or FFM as prediction factor, may be inaccurate. Furthermore, the physical activity energy expenditure can be affected. For single leg amputations, the level of amputation influences energy expenditure during walking (92). The energy cost of walking with a prosthesis is higher compared to regular walking, with transfemoral amputees showing a greater energy cost compared to transtibial amputees (93). Athletes walking with crutches have a higher energy cost of ambulation compared to controls (94), due to reduced stability requiring more energy to maintain balance, the involvement of both upper and lower limbs instead of just the lower limbs, and the rigidity of crutches, which creates a delay between foot and crutch landings compared to the fluid motion of normal walking (95). Other athletes with limb deficiencies make use of a wheelchair, which, as mentioned before, lowers the physical activity energy expenditure (44) and increases the risk for low bone mineral density.

Visual and hearing impairments

A fourth common condition is visual and hearing impairments. Athletes with visual or hearing impairments likely have a similar body composition to athletes without a disability. However, individuals with a visual impairment are often less physically active and spent more time being sedentary when compared with healthy adults (96). This is associated with a lower physically activity energy expenditure. However, this may not reflect to the athlete population. Furthermore, both daily life activities such as walking and sport activities such as running require extra

energy to perform (97), because visual input normally aids in the planning and correct execution of motor tasks. Visually impaired individuals must rely on other senses, such as hearing, touch, and proprioception to execute motor tasks. This leads visual impaired individuals to make shorter strides during both walking (98) and running (99), which decreases locomotion efficiency and increases energy expenditure (97) and energy requirements. Furthermore, for the visually impaired, the day and night cycles may be disrupted, leading to sleep disorders (100), especially in individuals with no light perception and sleep disorders influence metabolism (101). Additionally, choosing the right nutrition in a supermarket and preparing food (102) can be challenging for these athletes.

OUTLINE OF THESIS

Despite the growing Paralympic community, there remains a significant gap in our understanding of the unique nutritional requirements of Para athletes. While there is ample information on the nutritional needs of athletes without a disability, the nutritional requirements of Para athletes remain to be explored. This thesis describes a series of studies that explore the nutritional requirements of Paralympic athletes. In **Chapter 2** we used the gold standard doubly labeled water approach to gain advanced insight into the total daily energy expenditure of a large and diverse cohort of Paralympic athletes. Moreover, we aimed to identify the main factors associated with total daily energy expenditure. The major component of the total daily energy expenditure is the RMR. Therefore, in **Chapter 3**, we assessed the RMR and its potential predictors in Paralympic athletes. Subsequently, we aimed to generate novel prediction equations, which can be used by practitioners for estimating the RMR in this specific population. A main determinant of energy expenditure is body size and composition. Moreover, frequent monitoring of body composition is an important aspect of dietary counseling. In daily practice, nutritionists or dieticians often rely on skinfold measurements for the assessment of body composition. In **Chapter 4,** we examined the feasibility and validity of standardized skinfold thickness assessment against the dual energy x-ray absorptiometry as reference method. Besides fat mass and FFM, bone mineral density is also an important factor in body composition. Additionally, various disabilities potentially impact bone mineral density and bone quality of Para athletes either directly or indirectly. Therefore, in **Chapter 5**, we assessed the bone mineral density of Paralympic athletes. This study provides insights into the current bone mineral density

status and potential factors associated with impaired bone health in this population. An upcoming tool to support dietary counseling in athletes is continuous glucose monitoring. Therefore, in **Chapter 6** we explored the glucose profiles of Para cyclists using continuous glucose monitoring to identify potential opportunities for improved dietary counseling. Finally, the results of the studies described in this thesis are discussed in a broader context and implications for future research are provided in **Chapter 7**.

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Chapter 2

Energy requirements of Paralympic athletes: insights from the doubly labeled water approach

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ABSTRACT

Advanced insight in energy requirements of Paralympic athletes is imperative for optimizing their nutritional counseling. Given the lack of accurate data on total daily energy expenditure (TDEE) of Paralympic athletes, this study aimed to assess energy expenditure and nutritional intake of a large cohort of Paralympic athletes, across different sports and disabilities. In this cross-sectional study, 48 Dutch and Norwegian Paralympic athletes (19 male/29 female) with various disabilities, competing in Para cycling, wheelchair tennis, wheelchair basketball, Para Nordic skiing and alpine skiing participated. TDEE was assessed by the gold standard doubly labeled water method over a 14-day period, resting metabolic rate (RMR) by ventilated hood indirect calorimetry, energy intake (EI) by three unannounced 24h-dietary recalls, body composition by dual energy x-ray absorptiometry and exercise training duration by a training log. Mean TDEE was 2908±797 kcal/day, ranging from 2322±340 kcal/day for wheelchair basketball players to 3607±1001 kcal/day for Para cyclists. Regression analysis identified fat-free mass, exercise duration, and the presence of a spinal cord disorder as the primary predictors of TDEE, explaining up to 73% of the variance in TDEE. Athletes' EI (2363±905 kcal/day) was below their TDEE, while their body mass remained constant, indicating underreporting. Carbohydrate intake (4.1±1.9 g/kg body mass) was low, even when considering underreporting, while protein intake (1.8±0.6 g/kg body mass) was relatively high. Paralympic athletes display moderate to high energy expenditure, varying across sports and individuals. Much of the variation in TDEE can be attributed to individual differences in fat free mass and exercise duration. This study establishes the benchmarks for energy requirements of Paralympic athletes, serving as the foundation for future dietary guidelines within this population.

INTRODUCTION

Despite a wealth of information available on energy requirements of athletes across various sport disciplines, little information is available on the energy requirements of Paralympic athletes. Notably, no assessments of the energy requirements have been made by the gold standard doubly labeled water (DLW) approach. Currently, estimates of total daily energy expenditure (TDEE) in disabled athletes are limited to measurements or estimations of resting metabolic rate (RMR) with an activity allowance based on activity logs (1–3). However, this approach is complicated by the limited information on the energy costs of exercise and habitual physical activity in disabled athletes, potentially leading to inaccurate TDEE estimates. This warrants attention, given the potential differences in energy requirements between Paralympic athletes and their able-bodied counterparts.

Paralympic athletes may have a lower fat-free mass (FFM) due to factors like amputations or muscle degeneration from nerve innervation loss (e.g. spinal cord injury (SCI) or spina bifida (SB)), potentially affecting their absolute energy requirements (4). In support, individuals with SCI have been reported to have a lower RMR when compared to matched controls (5). In contrast, athletes with cerebral palsy or SCI may experience spasms, during which involuntary muscle contractions could potentially increase RMR (6). Furthermore, gait imbalances or ambulation with braces or crutches may increase the physical activity energy expenditure (PAEE) (7, 8), while for wheelchair users the energy costs of habitual physical activities, such as dusting, grocery shopping or vacuuming, are generally lower compared with able-bodied individuals (9). Additionally, the exercise energy expenditure has been shown to be lower in SCI athletes compared with able-bodied athletes, which could be due to lower peak oxygen uptakes (VO_{2peak}) (10), the amount of active muscle mass used, and lower maximal heart rates (11).

The energy requirements of athletes largely determine the macronutrient needs, i.e. carbohydrates, fats and proteins. The current macronutrient intake guidelines for Paralympic athletes are largely based on nutritional guidelines for abled-bodied athletes (12). Hence, the recommended carbohydrate intake for Paralympic athletes ranges from 3-5 g/kg body mass on days with low exercise volume up to 8-12 g/kg body mass on days with high exercise volume, while the recommended protein intake ranges from 1.2-1.8 g/kg body mass (13). Studies evaluating macronutrient intake in Paralympic athletes based on these guidelines (14-16) generally indicated inadequate energy and carbohydrate intakes compared with the recommendations. It should be noted, however, that neither energy nor carbohydrate intakes of Paralympic athletes has been evaluated in the light of the total energy requirements. Hence, it is unknown whether current guidelines are feasible within the energy budget of Paralympic athletes.

To gain advanced insight in the energy requirements of Paralympic athletes, we assessed energy expenditure and dietary intake in a large cohort of Paralympic athletes participating in diverse sports, encompassing athletes with a broad spectrum of disabilities. For this purpose, TDEE was assessed in Paralympic athletes by the DLW method, along with the assessment of RMR by indirect calorimetry and energy and macronutrient intake by multiple 24h-recalls.

METHODS

Design

The current cross-sectional study involved assessments of TDEE, dietary intake and training load assessed over a 14-day period, while RMR and body composition measurements were conducted on a single test day within one month. The 14-day period was selected in consultation with the coaching staff, aiming to reflect a representative training period. The study was pre-approved by the Medical Ethical Committee Zuyd (NL72682.096.20) in the Netherlands and the Regional Committee for Medical and Health Research Ethics (REK 102284) in Norway, and conducted according to the principles of the Declaration of Helsinki. All participants signed a written informed consent form before participation.

Participants

In this study, 48 male (*n*=19) and female (*n*=29) Paralympic athletes participated. These athletes competed in Para cycling (*n*=13, male/female: 8/5), wheelchair tennis (*n*=10, male/female: 5/5), wheelchair basketball (*n*=13, male/female: 0/13), Para Nordic skiing (*n*=7, male/female: 4/3) and Para alpine skiing (*n*=5, male/female: 2/3). The Nordic skiers, one Para cyclist and one alpine skier originated from and were measured in Norway, while all other athletes were Dutch and measured in the Netherlands. Participants (16–50 y) competing at the highest (inter)national level, were recruited through ongoing partnerships with the Dutch Olympic Committee and Norwegian national sport associations. Multiple disabilities were included, ranging from SCI to visual impairments (Table 2.1). The athletes were classified as being wheelchair users if more than 50% of their ambulatory activities outside of sports where performed in a wheelchair. Exclusion criteria were pregnancy or an injury that disrupted the regular training schedule. The participants were in preparation for either the 2020 Summer Paralympics in Tokyo or the 2022 Winter Paralympics in Beijing and won a total of 20 medals (11 gold, 4 silver and 7 bronze) during these games.

Resting metabolic rate

Participants arrived at the lab by car or public transport between 7:30 and 9:00 in an overnight fasted state. The RMR was measured by indirect calorimetry using a ventilated hood (Q-NRG, Cosmed, Italy for the Dutch participants, and Oxycon Pro, Jaeger System, Germany for the Norwegian participants). Before each test, the indirect calorimetry device was calibrated according to the manufacturer's instructions. The RMR measurements were conducted in a quiet room in thermoneutral conditions (~22.5 °C). Participants were rested in seated position for at least 20 min before being placed on a bed in supine position. The RMR measurements were conducted over a 30 min period with data points being collected every 30 s. RMR was determined as follows. The first 5 min of data were discarded. From the remaining 25 min, the average energy expenditure was determined, but only if the average variation in VO_2 and VCO_2 was lower than 10%. If the variation in VO_2 or VCO_2 exceeded 10%, the duration of the measurement was reduced with 5-min increments until a period with a variation below 10% was obtained (e.g., 20, 15, 10, or 5 min). If even the shortest 5-min interval displayed a variation above 10%, steady state was considered absent and the measurement was excluded from the analysis.

Body composition

After the RMR measurement, participants' body composition was assessed with a whole-body dual energy x-ray absorptiometry (DXA) scan. Three DXA systems were used in the current study, i.e. Hologic Horizon and Hologic Discovery A (Hologic, MA, USA) in the Netherlands and Lunar iDXA (GE Healthcare, Madison, USA) in Norway. Whole-body fat and FFM were determined with the participants positioned according to NHANES procedures (17, 18). If the procedures could not be followed due to a disability, participants were placed in a position they could maintain for the duration of the scan. Analyses were conducted using the system's software package (Hologic Horizon: Apex version 5.6.0.5, Hologic Discovery A: Apex version 4.5.3, Lunar iDXA: enCORE version 18). The height of the participants was measured with a stadiometer (Seca 213i and Seca 437, Hamburg, Germany) with an accuracy of 0.001 m. If the participant was unable to stand upright due to a disability, the height was measured in supine position measuring the height from heel to the top of the head with a tape measure. Body mass was measured with a scale (Seca 770 and Seca 887, Hamburg, Germany) with an accuracy of 0.1 kg.

Table 2.1. Participant characteristics.

	Total (*n*=48)	Para cycling (*n*=13)	Wheelchair tennis (*n*=10)	Wheelchair Basketball (*n*=13)	Nordic skiing (*n*=7)	Alpine skiing (*n*=5)
Male/Female	19/29	8/5	5/5	0/13	4/3	2/3
Disability *n*						
Spinal cord disorder	17	2	4	7	2	2
Neurological disorder	4	2	0	0	2	0
Limb deficiency	16	4	5	4	1	2
Visual impairment	4	2	0	0	1	1
Other	7	3	1	2	1	0
Wheelchair user (no/yes)	22/26	9/4	2/8	5/8	4/3	2/3
Age (years)	27 (23-33)	28 (24-32)	29 (23-36)	27 (21.5-33.5)	23.0 (19.0-34.0)	33 (21-38)
Body height (cm)	169.1 (160.8-180.0)	177.9 (164.2-190.9)	169.5 (147.4-177.6)	170.0 (141.5-181.1)	165.0 (151.1-180.0)	171.1 (146.4-181.3)
Body mass (kg)	63.2 (55.4-72.1)	70.6 (59.4-72.4)	65.2 (54.5-72.7)	60.0 (54.6-73.7)	59.2 (51.0-72.5)	63.3 (57.5-69.7)
BMI (kg/m^2)	22.4 (19.9-26.1)	22.1 (20.0-25.7)	23.4 (21.4-27.8)	21.7 (18.6-32.5)	22.4 (22.0-24.3)	19.6 (18.4-34.1)
Body fat (%)	23.2±8.5	17.8±6.8	22.3±6.2	27.4±8.3*	25.3±9.2	25.4±10.5
Fat free mass (kg)	49.2±10.0	54.5±12.1	48.6±8.2	46.1±8.5	47.3±10.9	46.7±7.1
Exercise duration (min/day)	104±41	103±35	129±46	71±13$^{\$}$	125±26	61±15$^{\$}$

Frequencies are presented as number of cases (n). Normally distributed data are presented as mean±SD, while non-normally distributed data are presented as median (Q1-Q3). BMI: body mass index.

*Significantly different from Para cycling $P < 0.05$.

$^{\$}$Significantly different from wheelchair tennis $P < 0.05$.

Total daily energy expenditure

The TDEE was assessed over a 14-day period by the DLW method according to the Maastricht protocol (19). In brief, before ingesting the DLW the participants provided a baseline urine sample on day 0. All participants received a dose of $^{2}H_{2}{}^{18}O$, based on their individual BMI, age and sex (20), targeting an initial body water enrichment of ~130 ppm for ^{2}H and ~230 ppm for ^{18}O. The participants ingested the DLW on day 0 at ~22:00 h, before going to bed. Participants measured and recorded their body mass on day 1, 8 and 15 directly after voiding, but before breakfast. Urine samples of the second void of the day were collected by the participants on days 1, 8 and 15. For validation purposes, a second urine sample was taken on these days at least 3 h after the first sample. All exact time points of the urine samples were recorded. Urine samples were either frozen immediately or stored in a refrigerator (~4 °C) and collected by the researcher within 36 h. Urine was aliquoted into two 2 mL glass vials and stored at -20°C. All samples were analyzed by isotope ratio mass-spectrometry (IRMS) at Maastricht University, the Netherlands. A regression line of the elimination of ^{18}O and ^{2}H was made from the 6 samples (not the baseline sample). Based on this regression line the ratio of elimination of ^{18}O and ^{2}H was calculated, from which the CO_2 production was calculated. TDEE was calculated from the CO_2 production where a respiration quotient of 0.85 was assumed. Furthermore, the isotope dilution spaces were calculated using the intercept method, meaning that the regression line obtained from all urine samples post-dosing was extrapolated back to time 0 (21).

Physical activity energy expenditure, physical activity level.

The PAEE was calculated as TDEE minus the diet induced thermogenesis (DIT) and measured RMR. The DIT was assumed to be 10% of the TDEE (22). Furthermore, the PAL of the participants was calculated as TDEE divided by RMR.

Nutritional analysis

The dietary intake of the participants was assessed by three unannounced 24h-dietary recalls. The recalls were conducted for a competition day, training day and rest day, when applicable. If no competition days were available within the 14-day period, recalls were conducted for two training days and one rest day. The recalls were conducted via video calls by nutritionists or dietitians who were specifically trained for this task. To increase accuracy, the recalls were assessed with the validated 5-step

multipass method with a checklist at the end (23). The raw data was processed with Compl-eat software (Wageningen University, Division of Human Nutrition) in the Netherlands and Kostberegningssystem (version 7.4, KBS, Oslo) in Norway, by a single researcher in each country respectively. The number of competition, training, and rest days were not equally distributed over the 14-day period. Therefore, weighted means, taking into account the number of competition, training and rest days for each individual, were calculated to estimate the mean daily energy and macronutrient intake over the 14-day period.

Exercise training

All participants were asked to keep a training log with information on the timing, type and duration of all training sessions or competitions during the 14-day period. Some participants already tracked such data in a digital app, while the other participants were provided a written training log to record training data. Exercise duration was extracted from all exercise training logs and mean daily exercise duration served as a universal exercise training metric across sports.

Statistical analysis

All data were analyzed with SPSS (IBM SPSS Statistics, version 27) and checked for normal distribution. Normal distributed data were described as mean±SD, whereas non-normal distributed data were described as median (Q1-Q3). The difference in TDEE, RMR, PAEE, PAL, energy- and macronutrient intake between the different sports disciplines were analyzed with a one-way Anova with Bonferroni correction. Since it was not feasible to perform a 24h-recall on a rest, training and competition day for all athletes, the differences in energy and macronutrient intake between the various days (rest, training, competition days) were analyzed with a paired t-test with multiple comparisons correction. Pearson correlations were conducted between energy expenditure (TDEE, RMR, PAEE) and FFM and exercise duration. Multiple regression analyses with backward selection were conducted with TDEE, PAEE and PAL as dependent variables. Exercise duration, FFM, age, the presence of spasms and the presence of spinal cord disorders (SCI or SB) were included as independent variables. Exercise duration was not recorded properly by 12 athletes, while FFM could not be assessed in one other athlete. Therefore, the regression analyses were performed with 35 athletes. Based on the regression analyses, three prediction equations for TDEE were formulated. The prediction equations were analyzed for accuracy by calculating the proportion of athletes within 10% of measured TDEE and the root

mean square error (RMSE) of the predicted TDEE. Statistical significance was set at $P< 0.05$.

RESULTS

Athlete characteristics

The physical characteristics of the participants are shown in Table 2.1. Participants were classified as either having a spinal cord disorder (SCD; including SB, traumatic and non-traumatic SCI; ranging from T4 to L3 complete and incomplete lesions; n=17;), neurological disorder (including cerebral palsy and other neurological disorders; n=4), limb deficiency (including dysmelia and amputations; n=16), a visual or hearing impairment (n=4) or other disabilities (n=7). Among the seven athletes in the other disabilities group were athletes with nerve damage in the lower extremities, hip dysplasia, muscular dystrophy, complex regional pain syndrome, or a connective tissue disease. Of all participants, 54% were classified as wheelchair users.

Exercise expenditure

During the 14-day period of TDEE measurements of the wheelchair basketball players, one of the players got infected by Covid and the whole team was quarantined from day 11. Therefore, only day 1 to 8 were analyzed for the TDEE of the wheelchair basketball players, except for one player who started the 14-day period one month later because of personal circumstances.

Results on energy expenditure are reported in Table 2.2. The mean RMR of participants was 1484±277 kcal/day. The RMR correlated strongly with the TDEE (r=0.73; P<0.001) and with the FFM (49.2±10.0 kg; r=0.80; P<0.001). When expressing the RMR relative to FFM, no significant differences between sports were observed.

Mean TDEE of all athletes was 2908±797 kcal per day (Figure 2.1A and Table 2.2). Para cyclists had a significantly higher TDEE compared with wheelchair basketball players (P<0.001) and alpine skiers (P=0.025). TDEE of wheelchair tennis players and Nordic skiers was not significantly different from any other sports category. The TDEE correlated strongly with the FFM (r=0.76; P<0.001). When expressed relative to FFM (Figure 2.1B), both Para cyclists and wheelchair tennis players exhibited a higher energy expenditure compared to wheelchair basketball players (P<0.01 for

both comparisons). Nordic skiers and alpine skiers did not significantly differ from any other sport. When comparing the various disabilities, SCD athletes (2379±522 kcal/day) exhibited a lower TDEE compared to both athletes with a limb deficiency (3140±837 kcal/day; P=0.027) and visual impaired athletes (3882±1003 kcal/day; P=0.003). However, no differences were found when TDEE is expressed relative to FFM. Furthermore, TDEE expressed relative to FFM correlated moderately with the exercise duration (r=0.50; P=0.002).

Table 2.2. The various components of energy expenditure.

	Total	Para cycling	Wheelchair tennis	Wheelchair basketball	Nordic skiing	Alpine skiing
TDEE (kcal/day)	2908±797	3607±1001	3082±381	2322±340*	2727±678	2521±256*
TDEE (kcal/kg FFM/day)	59.2±10.0	65.8±9.4	65.2±8.9	50.9±4.8*$	58.0±9.3	54.6±7.1
RMR (kcal/day)	1484±277	1683±276	1540±224	1374±203*	1258±283*	1412±246
RMR (kcal/kg FFM/day)	30.5±3.9	31.4±3.9	31.6±5.5	30.2±3.6	28.0±3.0	30.2±2.3
PAEE (kcal/day)	1127±555	1564±736	1234±317	715±210*	1117±410	857±244
PAEE (kcal/kg FFM/day)	22.9±8.6	27.8±9.8	27.0±5.3	15.6±4.1*$	24.8±7.6	18.9±7.0
PAL	2.0±0.4	2.1±0.4	2.0±0.3	1.7±0.2*	2.1±0.3	1.8±0.3

All outcomes are presented as mean±SD. Differences between sports categories were analyzed using one-way Anova. TDEE = total daily energy expenditure; FFM = fat free mass; RMR = resting metabolic rate; PAEE = physical activity energy expenditure; PAL = physical activity level.

*Significantly different from Para cycling $P < 0.05$.

$Significantly different from wheelchair tennis $P < 0.05$.

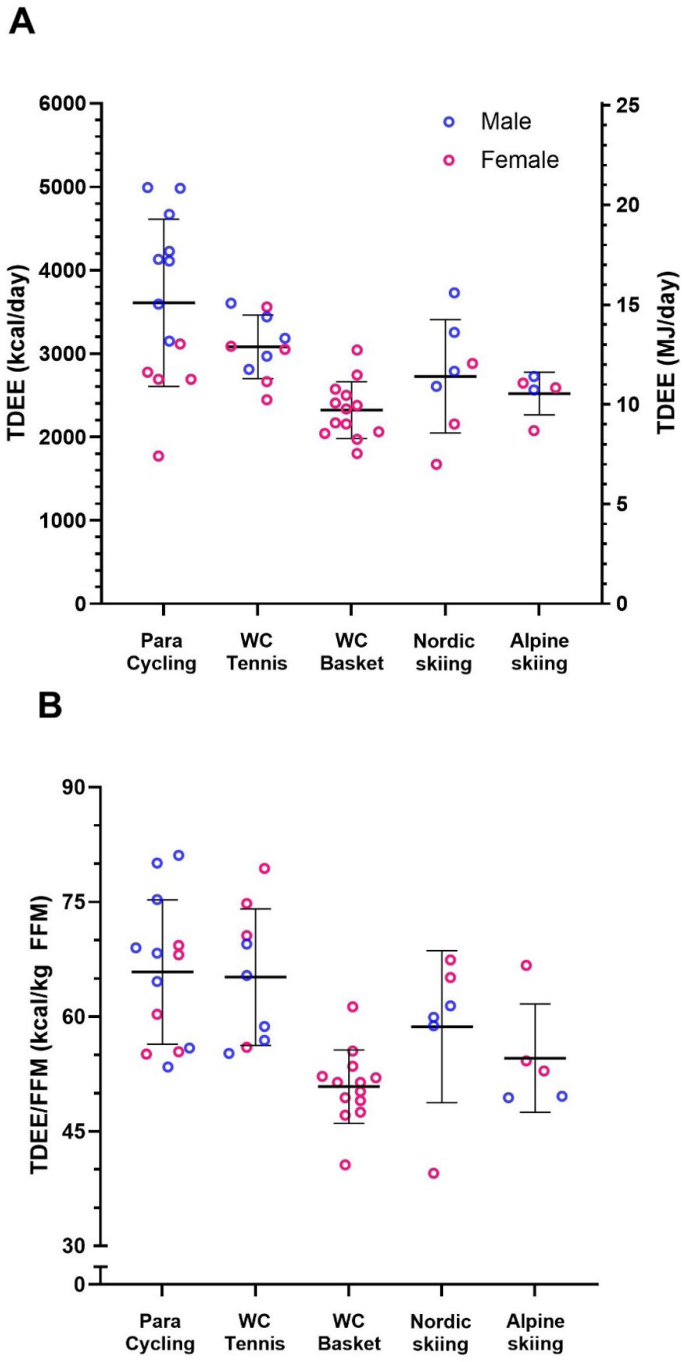

Figure 2.1. The absolute total daily energy expenditure (TDEE) (panel A) and TDEE divided by the fat-free mass (FFM) (panel B) for males (blue circles) and females (pink circles) categorized by sport. The horizontal lines and error bars represent the mean±SD for each sports category.

Mean PAEE of the Paralympic athletes was 1127±555 kcal. Again, Para cyclists had a significantly greater PAEE compared with wheelchair basketball players (P<0.01), while wheelchair tennis players, Nordic skiers and alpine skiers did not significantly differ from any other sport. When expressed relative to FFM, PAEE correlated moderately with exercise duration (r=0.60; P<0.001).

The mean PAL value of the Paralympic athletes was 2.0±0.4. However, large differences were observed between sports. Para cyclists showed the highest PAL value followed by Nordic skiers, wheelchair tennis players, alpine skiers and wheelchair basketball players. The PAL value correlated moderately with the exercise duration of the athletes (r=0.58; P<0.001).

Regression analyses

In the regression analyses presented in Table 2.3, it is shown that 73% of the variability in TDEE can be attributed to the independent variables FFM, exercise duration, and the presence of SCD. More specific, both FFM and exercise duration exhibited a positive relationship with TDEE, whereas SCD demonstrated a negative relationship. These variables were also responsible for explaining 62% of the variance in PAEE. With regard to PAL, FFM and exercise duration accounted for 42% of the variance.

Prediction of total daily energy expenditure

Based on the regression models, the TDEE can be predicted with three different prediction equations, in which TDEE and RMR are expressed in kcal/day, mean daily exercise duration in min/day, FFM in kg, and presence of SCD is binary (presence is 1, absence is 0):

Equation 1: Direct prediction of TDEE

*Predicted TDEE = −323.921 + (57.660 * FFM) + (6.203 * exercise duration) − (441.684 * SCD)*

Equation 2: Measured RMR with predicted PAEE and a 10% allowance for DIT (1.111)

*Predicted TDEE = (measured RMR + (−861.931 + (30.893 * FFM) + (6.345 * exercise duration) − (266.949 * SCD)))*1.111*

Equation 3: Measured RMR * predicted PAL

*Predicted TDEE = measured RMR * (0.975 + (0.011 * FFM) + (0.005 * exercise duration))*

Regressing the observed vs predicted TDEE resulted in R^2 values of 0.752, 0.799, and 0.773 for prediction Equation 1, 2, and 3 respectively (Figure 2.2). Prediction Equation 2 showed the highest accuracy, with 63% of the athletes predicted within 10% of the measured TDEE, while 20% and 17% were over- and underpredicted, respectively. Prediction Equation 1 and 3 predicted 60% and 51% correctly, respectively. The RMSE was lowest for Equation 2 at 272 kcal, followed by Equation 3 (312 kcal), and Equation 1 (314 kcal).

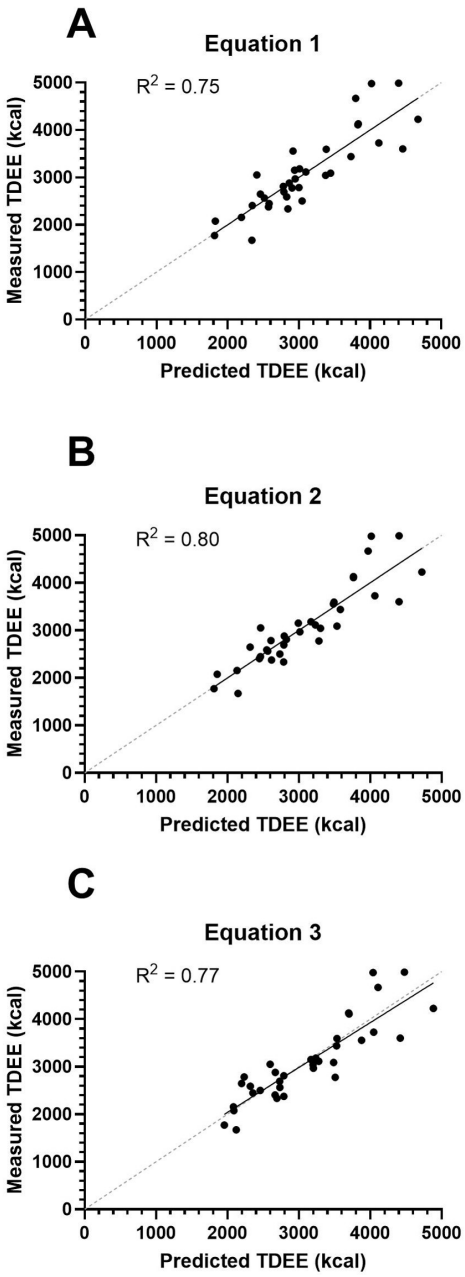

Figure 2.2. Predicted vs measured TDEE. TDEE was predicted according to three prediction equations, i.e. direct prediction of TDEE (panel A; Equation 1), TDEE predicted from measured RMR plus predicted PAEE+DIT (panel B; Equation 2), TDEE predicted from measured RMR multiplied with predicted PAL (panel D; Equation 3). The solid line represents the linear regression line of the prediction equations, with the corresponding R^2. The gray dashed line is the regression line through origin with a slope of 1.

Energy and macronutrient intake

As shown in Table 2.4, the weighted mean energy intake was 2363±905 kcal. As such, the energy intake was found to be 19±20% lower compared to the TDEE. As the athletes were relatively weight stable throughout the 14-day assessment period (65.8±11.5 kg on day 1 to 65.6±11.6 kg on day 15, median change -0.1 kg (IQR: -0.8 to +0.4), the discrepancy between energy expenditure and energy intake can be considered as underreporting rather than substantial undereating. When expressed relative to FFM, the weighted mean energy intake of wheelchair basketball players (34.5±9.9 kcal/FFM) was significantly lower compared to Para cyclists (56.2±15.2 kcal/FFM; $P<0.001$) and Nordic skiers (59.1±15.3 kcal/FFM; $P=0.002$). The energy intake of wheelchair tennis players (49.0±11.5 kcal/FFM) and alpine skiers (45.8±7.9 kcal/FFM) did not differ from any other sport. Although it was not feasible to conduct a 24h-recall on a rest, training and competition day for all participants, energy intake was numerically highest during competition days (2578±1444 kcal), followed by training days (2330±922 kcal) and rest days (2298±860 kcal). However, no significant differences were observed between different day types.

As shown in Table 2.4, the weighted mean carbohydrate intake was 4.1±1.9 g/kg body mass, while the mean protein intake was 1.8±0.6 g/kg body mass and the mean fat intake 32±6 % of energy intake. The carbohydrate intake per kg body mass was highest for Para cyclists followed by Nordic skiers, wheelchair tennis players, alpine skiers and wheelchair basketball players. Relative protein and fat intake did not significantly differ between the sport disciplines. With respect to the type of day, protein intake of the total group was significantly higher on training days compared to rest days ($P=0.012$). No differences in carbohydrate intake were found between type of days.

Table 2.3. Backward stepwise multiple regression model with total daily energy expenditure, physical activity energy expenditure and physical activity level as dependent variables.

Outcome variable: TDEE	Unstandardized Coefficients		Standardized Coefficients			
	B	Std. Error	Beta (β)	t	R^2_{adj}	*P*-value
Model					0.728	**<0.001**
(constant)	-323.921	463.041		-0.700		0.489
Exercise duration	6.203	1.809	0.307	3.430		**0.002**
Fat free mass	57.660	7.974	0.683	7.231		**<0.001**
Spinal cord disorder	-441.684	166.773	-0.250	-2.648		**0.013**
Outcome variable: PAEE+DIT	**Unstandardized Coefficients**		**Standardized Coefficients**			
	B	Std. Error	Beta (β)	t	R^2_{adj}	*P*-value
Model					0.634	**<0.001**
(constant)	-894.324	416.695		-2.146		**0.040**
Exercise duration	6.965	1.628	0.444	4.279		**<0.001**
Fat free mass	36.659	7.176	0.559	5.108		**<0.001**
Spinal cord disorder	-311.117	150.081	-0.227	-2.073		**0.047**
Outcome variable: PAEE	**Unstandardized Coefficients**		**Standardized Coefficients**			
	B	Std. Error	Beta (β)	t	R^2_{adj}	*P*-value
Model					0.617	**<0.001**
(constant)	-861.931	374.266		-2.303		**0.028**
Exercise duration	6.345	1.462	0.461	4.340		**<0.001**
Fat free mass	30.893	6.445	0.537	4.793		**<0.001**
Spinal cord disorder	-266.949	134.799	-0.222	-1.980		0.057

Table 2.3. Backward stepwise multiple regression model with total daily energy expenditure, physical activity energy expenditure and physical activity level as dependent variables. (*continued*)

Outcome variable: TDEE	Unstandardized Coefficients		Standardized Coefficients			
	B	Std. Error	Beta (β)	t	R^2_{adj}	*P*-value
Model					0.419	**<0.001**
(constant)	0.975	0.259		3.771		**<0.001**
Exercise duration	0.005	0.001	0.600	4.627		**<0.001**
Fat free mass	**0.011**	**0.005**	0.301	2.320		**0.027**

TDEE = total daily energy expenditure; PAEE = physical activity energy expenditure; DIT = diet induced thermogenesis; PAL = physical activity level.

Table 2.4. Energy and Macronutrient intake

	Total	Para cycling	WC tennis	WC basketball	Nordic skiing	Alpine skiing
Weighted mean						
n	48	13	10	13	7	5
Energy (kcal)	2363 ± 905	3062 ± 1029^	2322 ± 490	1554 ± 402	2776 ± 853^	2152 ± 518
Carbohydrate (g)	263 ± 127	369 ± 141^	259 ± 99	155 ± 51	300 ± 116^	228 ± 49
Carbohydrate (g/kg BM)	4.1 ± 1.9	5.5 ± 1.9^	4.1 ± 1.7	2.5 ± 0.9	4.9 ± 2.0^	3.6 ± 0.6
Protein (g)	118 ± 41	139 ± 39	113 ± 51	99 ± 29	121 ± 41	118 ± 41
Protein (g/kg BM)	1.8 ± 0.6	2.1 ± 0.5	1.7 ± 0.7	1.6 ± 0.5	2.0 ± 0.7	1.9 ± 0.8
Fat (g)	85 ± 37	106 ± 40^	84 ± 24	54 ± 17*$	114 ± 42^	76 ± 27
Fat (EN%)	32 ± 6	31 ± 6	32 ± 6	31 ± 7	37 ± 5	31 ± 5
Rest day						
n	32	8	7	10	3	4
Energy (kcal)	2298 ± 860	2956 ± 1001^	2410 ± 722	1779 ± 422	2249 ± 1344	2118 ± 634
Carbohydrate (g)	246 ± 104	327 ± 114^	251 ± 95	177 ± 47	259 ± 177	240 ± 47
Carbohydrate (g/kg BM)	3.9 ± 1.7	5.0 ± 1.6	4.0 ± 1.6	2.8 ± 0.9	4.4 ± 3.5	3.7 ± 0.7
Protein (g)	110 ± 35[a]	133 ± 26	105 ± 41[a]	105 ± 26	90 ± 43	97 ± 44[a]
Protein (g/kg BM)	1.7 ± 0.6[a]	2.1 ± 0.4	1.7 ± 0.6[a]	1.6 ± 0.5	1.5 ± 0.8	1.5 ± 0.7[a]
Fat (g)	89 ± 45	114 ± 55	100 ± 42	66 ± 34	88 ± 53	80 ± 42
Fat (EN%)	34 ± 9	34 ± 8	37 ± 8	32 ± 10	35 ± 9	32 ± 13
Training day						
n	48	13	10	13	7	5
Energy (kcal)	2330 ± 922	2992 ± 975^	2312 ± 494	1483 ± 448	2806 ± 1014^	2178 ± 519

Table 2.4. Energy and Macronutrient intake (*continued*)

	Total	Para cycling	WC tennis	WC basketball	Nordic skiing	Alpine skiing
Carbohydrate (g)	260 ± 127	359 ± 130^	254 ± 111	151 ± 57	303 ± 125^	232 ± 74
Carbohydrate (g/kg BM)	4.0 ± 1.9	5.3 ± 1.7^	4.0 ± 1.9	2.5 ± 1.0	4.9 ± 2.0^	3.6 ± 0.9
Protein (g)	120 ± 44	136 ± 42	120 ± 57	100 ± 37	123 ± 43	128 ± 37
Protein (g/kg BM)	1.9 ± 0.7	2.0 ± 0.6	1.9 ± 0.8	1.6 ± 0.6	2.0 ± 0.7	2.0 ± 0.7
Fat (g)	83 ± 39	104 ± 43^	83 ± 23	47 ± 14	115 ± 45^	75 ± 21
Fat (EN%)	32 ± 7	31 ± 7	32 ± 6	29 ± 7	37 ± 6	31 ± 3
Competition day						
n	20	6	0	11	3	0
Energy (kcal)	2578 ± 1444	4168 ± 1569^	N.A.	1669 ± 519	2731 ± 374	N.A.
Carbohydrate (g)	305 ± 227	562 ± 257^	N.A.	166 ± 61	300 ± 43	N.A.
Carbohydrate (g/kg BM)	4.6 ± 3.1	8.1 ± 3.4^	N.A.	2.6 ± 1.0	5.0 ± 1.2	N.A.
Protein (g)	124 ± 51	172 ± 42^	N.A.	98 ± 43	122 ± 22	N.A.
Protein (g/kg BM)	1.9 ± 0.7	2.5 ± 0.5^	N.A.	1.5 ± 0.6	2.0 ± 0.4	N.A.
Fat (g)	88 ± 42	125 ± 48^	N.A.	62 ± 21[a]	108 ± 14	N.A.
Fat (EN%)	32 ± 6	27 ± 5	N.A.	33 ± 5	35 ± 2	N.A.

Data is presented as mean±SD or number of athletes included. Differences in energy and macronutrient intake between sports within day type were analyzed using one-way Anova. Differences in energy and macronutrient intake between day types within sports were analyzed using paired t-tests with multiple comparisons corrections.

^ Significantly different from wheelchair basketball $P < 0.05$. [a] Significantly different from training day within group $P < 0.05$. WC = wheelchair; kg BM = kilogram body mass; EN% = energy percentage

DISCUSSION

The current study aimed to assess energy expenditure and intake of a large cohort of Paralympic athletes, across different sports and disabilities. The TDEE was moderate to high, ranging from 2322±340 kcal/day for wheelchair basketball players to 3607±1011 kcal/day for Para cyclists. Regression analysis identified FFM, exercise duration, and SCD as the primary predictors of TDEE. Athletes' EI and carbohydrate intake were relatively low, while protein intake was sufficient.

Energy expenditure

No previous studies have assessed the TDEE using the DLW approach in a representative group of Paralympic athletes. Our data revealed an average TDEE of approximately 2900 kcal/day, which aligns with a recent case study of a wheelchair tennis player, where the TDEE measured by DLW was reported to be between 3118 and 3368 kcal/day (24). These TDEE data of Paralympic athletes are considerably higher than estimates of the energy requirements derived from analyzing the energy intake of weight-stable athletes with SCI (16) and wheelchair athletes (14), with energy intakes ranging from 1500 to 2300 kcal/day. Therefore, the novel, high-quality data provided by the DLW approach in our study indicate that previous literature relying on EI may have severely underestimated the actual energy requirements of Paralympic athletes.

FFM was the strongest predictor for both TDEE and PAEE in the multiple regression analyses. The major contribution of FFM to the energy expenditure can be explained by the high metabolic activity of the tissues it encompasses, including vital organs and skeletal muscle (25). In addition to FFM, the mean daily exercise duration was identified as a significant predictor of TDEE, PAEE and PAL. While it may seem intuitive that a higher exercise duration would lead to an increased TDEE, the constrained energy expenditure model proposed by Pontzer and colleagues (26) suggests that as daily physical activity levels rise, other energy-demanding processes are downregulated, resulting in only minimal impact on TDEE. However, in contrast, the current study's linear correlation (r=0.51) between the exercise duration and TDEE (relative to FFM) suggests a largely additive effect of physical activity on TDEE. It could even be speculated that exercise volume, as a product of exercise duration and intensity, would explain even more of the variation in PAEE and TDEE than exercise duration alone. However, due to the diverse range of sport disciplines and training regimens in our study and the challenges as-

sociated with objectively measuring exercise intensity, it was not feasible to collect uniform data on exercise intensity and, consequently, exercise volume.

Previous literature reported that individuals with SCI exhibit a lower RMR compared to controls (5), which likely translates to a lower TDEE as well. While some studies completely attribute the lower RMR to low FFM (27, 28), others have shown that the reduced RMR in individuals with SCI (5) and SB (29) extends beyond low FFM. In agreement, we found that individuals with SCD exhibited a lower TDEE, even when accounting for FFM. One explanation could be a decreased sympathetic nervous system activity in individuals with SCD (30). As shown by pharmacological intervention studies with β-adrenergic blockers, a reduced sympathetic nervous system activity leads to a lower overall metabolic rate (31, 32) and thus lower TDEE. Another explanation is a reduction in exercise energy expenditure. Previous studies have reported that athletes with SCI exhibit lower maximal heart rates (11), and VO_{2peak} (10) during exercise compared to able-bodied elite athletes. This leads to a lower exercise energy expenditure at the same relative exercise intensity (i.e. a percentage of VO_{2peak} or heart rate) compared to able-bodied athletes (11) and likely also compared with disabled athletes without SCD.

In this study, the TDEE was assessed by the DLW method, providing an accurate measurement of the TDEE. However, due to the high costs associated with this measurement method, it is not feasible for routine use in daily practice. To allow for estimations of TDEE in Paralympic athletes, by using practical, easy-to-use methods, we developed prediction equations based on prediction factors that are relatively easy to obtain by practitioners. In this regard, the preferred equation to predict the TDEE relies on the measured RMR together with the predicted PAEE (Equation 2), in which FFM, exercise duration and the presence of SCD are used to predict the PAEE. If RMR cannot be assessed accurately, TDEE can also be predicted directly based on FFM, exercise duration, and the presence of SCD (Equation 1). Both equations presented an accuracy above 60%, with Equation 2 exhibiting a slightly higher accuracy compared to Equation 1. These findings are promising, suggesting that the newly developed equations hold potential as tools for estimating TDEE in Paralympic athletes. It is important to acknowledge, however, that the evaluation of the accuracy was conducted with the same cohort of athletes, whose characteristics were used for the initial regression analyses. This might have inflated the predictive accuracy (33).

Energy intake

The 19% underreporting of energy intake observed in the current study is commonly seen in nutrition research (34), and underlines that energy intake data should be evaluated with caution. While the common sport nutritional guidelines (13) and those specific for Para cyclists (35) indicate that carbohydrate intake should be tailored according to the daily needs, observed carbohydrate intakes were generally low and did not differ significantly between the different day types. Even when considering 19% underreporting, most athletes had inadequate carbohydrate intakes according to the guidelines. Multiple reasons for a low carbohydrate intake have been identified in previous studies, including inadequate practical nutrition skills or nutritional knowledge, poor availability of CHO-rich foods in the immediate eating environment, or a chaotic lifestyle with frequent travel commitments (36). However, the most important reason for low carbohydrate intake may be the desire to restrict energy intake for weight maintenance or loss (37). The use of the DLW method in the present study allows for the evaluation of carbohydrate intake in the light of TDEE. Considering the athletes' current protein intake (1.8 g/kg body mass) and the common sports nutrition recommendations for fat intake (30% of total energy intake), we can determine feasible carbohydrate intake levels based on the measured TDEE for various sports. Consequently, Para cyclists could aim for a mean daily carbohydrate intake of 6-10 g/kg body mass, while wheelchair tennis players could target 5-8 g/kg body mass. Nordic skiers should consider of 4-8 g/kg body mass, and alpine skiers and wheelchair basketball players could aim for 4-6 g/kg body mass.

The mean protein intake (1.8 g/kg body mass) was in the higher range of current sports nutrition guidelines for non-disabled athletes (1.2-1.8 g/kg body mass) (13). Furthermore, the protein intake was significantly higher on training days compared with rest days. It has been suggested that Paralympic athletes can benefit from a higher protein intake during the healing of ulcers (38). However, none of the participants reported to have ulcers during the measurement period and no other surplus benefits of a high protein diet have been demonstrated in Paralympic athletes yet. Altogether, our data suggest that the emphasis should be placed more on carbohydrates rather than protein.

Strengths and limitations

The main strength of this study is the use of the DLW method to assess energy requirements of Paralympic athletes. This is the first study to

provide such novel and valuable insights into the energy requirements of Paralympic athletes. Still, we should also acknowledge some limitations of this study that are also included in the interpretations of our results.

This international study was conducted at two different research sites to allow for a large number of Paralympic athletes to participate. However, RMR and FFM were assessed using different equipment at these sites. Standardized operating procedures were implemented across research sites to minimize potential measurement errors, although the risk for systematic errors between research sites cannot be completely eliminated.

The assessment of energy expenditure by DLW requires several assumptions. More specifically, to translate CO_2 production to energy expenditure, we assumed a respiratory quotient (RQ) of 0.85. However, the RQ could have been higher or lower based on the macronutrient composition of the diet of the participants. Another approach considered was calculating the food quotient (FQ) based on the nutritional intake and using that in the estimation of RQ (39). However, due to the 19% underreporting of EI and the possibility that carbohydrates are more susceptible to underreporting compared to fat and protein (40), the FQ and therefore the RQ would be biased. As a result, a single RQ value was used for all athletes, instead of individual values, which could have caused a small over- or underestimation of the TDEE of less than 5%. In addition, PAEE was derived from TDEE by subtracting RMR and DIT. While RMR was measured, DIT was assumed to be 10% of TDEE. Since the actual DIT may range between 5–15% of TDEE (22), PAEE may be slightly under- or overestimated.

Despite the relatively large cohort of male and female Paralympic athletes competing in various large Paralympic sports in the Netherlands and Norway, not all Paralympic sports were represented. Hence, the prediction equations generated in the current study were based on the athletes and sports included in this particular study. It remains to be established whether the prediction equations are also valid in other Paralympic populations comprising a wider selection of Paralympic sports.

The influence of wheelchair dependence on TDEE was not analyzed. Most of the athletes with SCD were wheelchair users (94%), while this proportion was substantially lower in other groups. Since SCD is a known

modulator of RMR and TDEE (5, 29), we selected SCD rather than wheelchair dependence as predictor of TDEE.

Conclusion

The energy expenditure of Paralympic athletes presented here can be regarded moderate to high, although substantial variations between sports and individuals are observed. Much of this variation in TDEE between sports and individuals can be attributed to individual differences in FFM and exercise duration, while the presence of SCD negatively affects TDEE. Consequently, we developed prediction equations that can estimate the TDEE of Paralympic athletes based on RMR, FFM, exercise duration and the presence of SCD. Regarding dietary intake, there is room to increase carbohydrate intake while maintaining energy balance. Furthermore, protein intake is relatively high for most Paralympic athletes. Taken together, this comprehensive study establishes the benchmarks for energy requirements of Paralympic athletes, serving as the foundation for future dietary guidelines and nutritional counseling within this population.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest, financial or otherwise, related to the present work. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine. Deidentified participant data are available upon reasonable request.

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Chapter 3

Measured and predicted resting metabolic rate of Dutch and Norwegian Paralympic athletes

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ABSTRACT

While the resting metabolic rate (RMR) is crucial for understanding athletes' energy requirements, limited information is available on the RMR of Paralympic athletes.

Objective: To determine RMR and its predictors in a diverse cohort of Paralympic athletes and evaluate the agreement between measured and predicted RMR from both newly developed and preexisting equations. This cross-sectional study, conducted between September 2020 and September 2022 in the Netherlands and Norway, assessed RMR in Paralympic athletes by ventilated hood indirect calorimetry and body composition by dual energy X-ray absorptiometry.

Participants: Sixty-seven Paralympic athletes (male: *n*=37; female: *n*=30) competing in various sports, with a spinal cord disorder (SCD; *n*=22), neurological condition (*n*=8), limb deficiency (*n*=18), visual or hearing impairment (*n*=7) or other disability (*n*=12) participated.

Main outcome measures: RMR, fat-free mass (FFM), body mass, and triiodothyronine (T3) concentrations were assessed. Multiple regression analyses were conducted with height, FFM, body mass, sex, T3 concentration, and disabilities as potential predictors of RMR. Differences between measured and predicted RMRs were analyzed for individual accuracy, root mean square error (RMSE), and intraclass correlation (ICC). Mean RMR was 1386±258 kcal/day for females and 1686±302 kcal/day for males. Regression analysis identified FFM, T3 concentrations and the presence of a spinal cord disorder (SCD), as the main predictors of RMR (adjusted R^2=0.71; F=50.3; *P*<0.01). The novel prediction equations based on these data, as well as pre-existing equations of Chun *et al*. and Nightingale and Gorgey performed well on accuracy (>60% of participants within 10% of measured RMR), had a good reliability (ICC >0.78), and low RMSE (≤141 kcal). FFM, total T3 concentrations, and the presence of SCD are the main predictors of RMR in Paralympic athletes. Both the current study's prediction equations and those by Chun et al. and Nightingale and Gorgey align well with measured RMR, offering accurate prediction equations for the RMR of Paralympic athletes.

INTRODUCTION

To provide effective nutritional counseling for athletes, a comprehensive understanding of their energy expenditure is essential. Generally, the resting metabolic rate (RMR) accounts for 60-70% of total daily energy expenditure.(1) Therefore, the assessment of the RMR forms the basis of determining the daily energy requirements of athletes.

Indirect calorimetry equipment, involving the assessment of oxygen consumption (VO_2) and carbon dioxide production (VCO_2), can be used for accurately assessing RMR.(2) However, indirect calorimetry is not always available in clinical practice, and measurements are expensive and time-consuming. Therefore, RMR is often estimated with prediction equations, based on readily available anthropometric and demographic variables such as fat-free mass (FFM) or body mass, body height, age, and sex. While these equations have been extensively evaluated for their accuracy to predict RMR in athletes without disabilities,(3, 4) it is imperative to acknowledge that Paralympic athletes may exhibit different RMR values compared to their counterparts without disabilities. Such disparities can, in part, be attributed to the unique body composition characteristics of Paralympic athletes. Specifically, when considering FFM as the primary predictor of resting energy expenditure,(5) it is noteworthy that Paralympic athletes may have limb deficiencies or a lack of nerve innervation. These factors not only lead to a reduction in absolute FFM, but also result in an altered ratio between skeletal muscle mass and internal organ mass. (6) Moreover, the denervation of the sympathetic nervous system (SNS) in athletes with a spinal cord injury (SCI)(7) and possibly spina bifida, may lead to impairments in sympathetic nerve system activity, which in turn, decrease catecholamine levels,(8) heart rate, blood pressure,(9) thermogenesis(10) and, thyroid hormone levels,(11) and may, therefore, also lower RMR.(12) Furthermore, conditions such as athetosis,(13) hypertonia,(14) and spasms,(15) which are prevalent among athletes with cerebral palsy, may elevate RMR.

Given the unique physical and physiological characteristics of Paralympic athletes, it seems evident that current RMR prediction equations developed for non-athletes or athletes without disabilities, may not provide accurate RMR estimates for the Paralympic population. For instance, in the study by Pelly et al.,(16) it was demonstrated that multiple prediction equations tended to overestimate RMR in athletes with SCI when compared with controls without disabilities. So far only Herrera-Amante

et al.(17) developed prediction equations based on fifteen Paralympic swimmers with various disabilities. However, these equations rely on anthropometric prediction factors (i.e. skinfolds, neck and chest girth, and statures) that are challenging to acquire and have not undergone validation in other Paralympic cohorts. Other prediction equations have been specifically developed for individuals with SCI,(18, 19) albeit in non-athletes. Nevertheless, these prediction equations appeared to underestimate the RMR of wheelchair rugby athletes with SCI by ~19%.(20) Such disparities between predicted and measured RMR highlight the need for tailored equations designed specifically for Paralympic athletes. Such prediction equations should not only address athletes with SCI, but should also consider the wider range of factors that can potentially affect RMR in Paralympic athletes.

The current study evaluated the RMR and its potential predictors in a diverse cohort of Paralympic athletes from various sports. Furthermore, novel prediction equations for Paralympic athletes were developed. The predictive accuracy of both these newly developed equations and pre-existing equations was assessed by comparing measured and predicted RMR.

METHODS

Study design

In this cross-sectional study, RMR and its potential predictors were assessed in a large cohort of Paralympic athletes. This study was part of a larger collaborative study on the nutritional requirements of Paralympic athletes, of which the core paper has recently been published.(21) Data were collected between September 2020 and September 2022 at the sport and research center of the HAN University of Applied Sciences (Nijmegen, The Netherlands) and at the department of Physical Performance at the Norwegian School of Sport Sciences (Oslo, Norway). The study was approved by the Medical Ethical Committee Zuyd (NL72682.096.20) in the Netherlands and the Regional Committee for Medical and Health Research Ethics (REK 102284) in Norway.

Participants

A total of 70 Paralympic athletes competing in wheelchair basketball (n=17), Para cycling (n=16), wheelchair tennis (n=10), Para alpine skiing (n=8), Para Nordic skiing (n=7), Para swimming (n=4), wheelchair

rugby (*n*=2), boccia (*n*=1), Para badminton (*n*=1), Para orienteering (*n*=1), Para rifle shooting (*n*=1), Para snowboarding (*n*=1), and wheelchair racing (*n*=1) were recruited. The wheelchair basketball players, Para cyclists, wheelchair tennis players, Para swimmers, and seven Para alpine skiers were Dutch and were measured in the Netherlands, while all other athletes were Norwegian and were measured in Norway. Participants competing at the highest (inter)national level were recruited through ongoing partnerships with Dutch and Norwegian Paralympic Committees and national sport associations. We aimed to include as many Paralympic athletes as possible from the pool of Paralympic athletes in the Netherlands and Norway. Exclusion criteria were pregnancy or an injury that disrupted their regular training regimen. The participants were in preparation for either the 2020 Summer Paralympics in Tokyo or the 2022 Winter Paralympics in Beijing, and won a total of 11 gold, 6 silver, and 8 bronze medals during those Paralympic games. All participants were informed about the nature and potential risks of the study and signed an informed consent according to code of ethics of the Declaration of Helsinki.

Resting metabolic rate

Participants arrived at the lab by car or public transport between 7:30 and 9:00 A.M. in an overnight fasted state. Before the RMR measurement, participants were interviewed about their medical history. This interview also included information about sex, age and the disability, including the presence of spasms and spinal cord disorders. The interview was performed while the participants were seated, and lasted more than 20 min. After the interview, RMR was assessed by indirect calorimetry using a ventilated hood (Q-NRG, Cosmed, Italy for the Dutch participants, and Oxycon Pro, Jaeger System, Germany for the Norwegian participants). Before each measurement, the indirect calorimetry device was calibrated according to the manufacturer's instructions. The RMR measurements were conducted in a quiet room in thermoneutral conditions (~22.5 °C) in supine position. The RMR measurements were conducted over a 30 min period with data points being collected every 30 s. RMR was determined as follows. The first 5 min of data were discarded. From the remaining 25 min, the average energy expenditure was determined, but only if the average variation in VO_2 and VCO_2 was lower than 10%. If the variation in VO_2 or VCO_2 exceeded 10%, the duration of the measurement was reduced with 5 min decrements until a period with a variation below 10% was obtained (e.g., 20, 15, 10, or 5 min). If even the shortest 5 min interval displayed a variation above 10%, steady state was considered absent and

the measurement was excluded from the analysis. The RMR was calculated based on the VO_2 and VCO_2 values by the equation of Weir.(22)

Body composition

After the RMR measurement, the body composition of the participants was assessed with a whole-body dual-energy x-ray absorptiometry (DXA) scan. Three DXA systems were used in the current study, i.e. Hologic Horizon and Hologic Discovery A (Hologic, MA,USA) in the Netherlands and Lunar iDXA (GE Healthcare, Madison, USA) in Norway. Whole-body fat and FFM were determined with the participants positioned according to NHANES procedures.(23, 24) If the procedures could not be followed due to a disability, participants were placed in a position they could maintain for the duration of the scan. Analyses were conducted using the system's software package (Hologic Horizon: Apex version 5.6.0.5,(25) Hologic Discovery A: Apex version 4.5.3,(26) Lunar iDXA: enCORE version 18(27)). The height of the participants was measured according to the International Society for the Advancement of Kinanthropometry (ISAK) standards(28) with a stadiometer (Seca 213i and Seca 437, Hamburg, Germany, for the Netherlands and Norway respectively) with an accuracy of ±0.1cm. If the participant was unable to stand upright due to a disability, the height was measured in supine position measuring the height from heel to the top of the head with a tape measure. Body mass was measured according to ISAK standards(28) with a scale (Seca 770 and Seca 887, Hamburg, Germany, for the Netherlands and Norway respectively) with an accuracy of ±0.1 kg.

Blood analysis

Fasted venous blood samples were taken from an antecubital vein. The blood samples were allowed to clot for ~30 min and centrifuged at 1000*g* for 15 min Subsequently, aliquots of serum were stored at −80°C, until further analysis. The samples were analyzed for triiodothyronine (T3), by the Central Diagnostic Laboratory at the Maastricht University Medical Centre (The Netherlands). Total T3 was determined with a chemiluminescent immunoassay (Immulite XPi instrument, Siemens Healthcare Diagnostics). Reliability (CV) for between-day measurements was ≤10%. Clinically low and high T3 were defined as <0.5 ng/mL (0.8 nmol/L) and >1.7 ng/mL (2.6 nmol/L),(29) respectively.

Data-analysis

All data were analyzed with SPSS (IBM SPSS Statistics, version 27)(30) and checked for normal distribution. Differences in RMR between groups classified according to disability were analyzed with a one-way Anova, or a Kruskal-Wallis test when the data were non-normally distributed. Multiple regression analyses with backward selection were conducted, with measured RMR as dependent variable and height, either FFM or body mass and sex, the presence of spasms, the presence of SCD, and T3 as independent variables. The estimated RMR derived from both novel and existing prediction equations (Table 3.1) (18, 19, 31-40) was evaluated against the measured RMR. Accuracy was determined as the proportion of individuals with an RMR within 10% deviation from the measured RMR. Additionally, the root mean square error (RMSE) and intraclass correlation (ICC) between the predicted and measured RMR were calculated. Furthermore, the 95% limits of agreement and bias were analyzed by Bland-Altman plots. Statistical significance was set at $P<0.05$.

Table 3.1. Prediction equations used.

Author	Prediction equation
1. Cunningham[31]	RMR = 500 + 22 * fat-free mass
2. Harris benedict[32]	
Male	RMR = 66.4730 + (13.7516 * body mass) + (5.0033 * height) – (6.7550 * age)
Female	RMR = 655.0955 + (9.5634 * body mass) + (1.8496 * height) – (4.6756 * age)
3. Roza and Shizgal[33]	
Male	RMR = 88.362 + (13.397 * body mass) + (4.799 * height) – (5.677 * age)
Female	RMR = 447.593 + (9.247 * body mass) + (3.098 * height) – (4.330 * age)
4. Spijker en Hoven[34]	RMR = (11.797 * body mass) + (6.487 * height)
5. Ten Haaf[35]	RMR = (11.936 * body mass) + (5.87728 * height) – (8.129 * age) + (191.027 * sex(M=1,F=0)) + 29.279
6. Mifflin st. Jeor[36]	
Male	RMR = (10 * body mass) + (6.25 * height) - (5 * age) + 5
Female	RMR = (10 * body mass) + (6.25 * height) - (5 * age) - 161
7. Owen[37]	
Male	RMR = 290 + (22.3 * fat-free mass)
Female	RMR = 50.4 + (21.1 * body mass)

Table 3.1. Prediction equations used. (*continued*)

Author	Prediction equation
8. Schofield[38]	
Male	RMR = 873.1 + (11.472 * body mass)
Female	RMR = 845.6 + (8.126 * body mass)
9. WHO[39]	
Male	
18–30 years of age	RMR = (15.4 * body mass) – (0.27 * height) + 717
31–60 years of age	RMR = (11.3 * body mass) + (0.16 * height) + 901
Female	
18–30 years of age	RMR = (13.3 * body mass) + (3.34 * height) + 35
31–60 years of age	RMR = (8.7 * body mass) – (0.25 * height) + 865
10. De Lorenzo[40]	RMR = (9.0 * body mass) + (11.7 * height) - 857
11. Chun[18]	RMR = 244.4 + (24.5 * fat-free mass)
12. Nightingale and Gorgey[19]	RMR = 294.330 + (23.469 * fat-free mass)

Body mass in kg; height in cm; fat-free mass in kg; age in years. M=male; F=female.

Table 3.2. Participant characteristics.

	All (*n*= 67)	Spinal cord disorders (*n*=22)	Neurological conditions (*n*=8)	Limb deficiency (*n*=18)	Visual or hearing impaired (*n*=7)	Other (*n*=12)
Sex (female/male)	30/37	9/13	5/3	9/9	4/3	3/9
Ethnicity or race (White/ Latin/Arab-White)	64/2/1	21/1/0	8/0/0	17/1/0	7/0/0	11/0/1
Age (years)	28 ± 9	31 ± 9	24 ± 5	27 ± 8	26 ± 9	29 ± 11
Height (cm)	165.9 ± 20.1	165.6 ± 16.8	172.9 ± 7.2	155.0 ± 28.1	179.2 ± 9.5	170 ± 15.2
Body mass (kg)	64.7 (55.7-72.5)	61.7 (52.8-67.4)	67.3 (56.5-74.3)	63.3 (53.5-70.8)	73.8 (70.5-86.2)	65.2 (59.8-78.2)
Fat-free mass (kg)	49.2 ± 10.6	44.8 ± 8.2	50.0 ± 7.9	48.9 ± 9.2	59.3 ± 10.3*	50.9 ± 14.2
T3 (ng/mL)	0.95 ± 0.21	0.96 ± 0.22	0.96 ± 0.23	0.92 ± 0.21	0.90 ± 0.18	0.99 ± 0.23
Spasms (yes/no)	16/54	8/14	7/1	0/18	0/7	1/11
RMR (kcal/day)	1520 ± 315	1366 ± 241	1581 ± 316	1512 ± 268	1744 ± 347*	1646 ± 379
RMR/body mass (kcal/ kg body mass)	23.2 ± 3.4	22.4 ± 3.3	23.6 ± 2.8	24.3 ± 3.5	22.6 ± 4.9	23.3 ± 3.1
RMR/Fat-free mass (kcal/kg FFM)	31.1 ± 4.3	30.4 ± 4.0	31.6 ± 3.9	31.3 ± 4.7	29.4 ± 3.6	32.9 ± 4.8

Data presented as mean±SD or median (Q1-Q3). * = significantly different from spinal cord disorder (P = 0.02). RMR = resting metabolic rate. T3 = Triiodothyronine.

RESULTS

Participants

Out of the seventy athletes that were recruited, three participants were excluded from the analysis due to the absence of an RMR steady state. The remaining 67 participants were categorized based on their disabilities as follows: Spinal cord disorders (SCD; including spina bifida and traumatic and non-traumatic SCI; ranging from T4 to L3 complete and incomplete lesions; *n*=22), neurological conditions (NC; including cerebral palsy and other neurological disorders; *n*=8), limb deficiencies (LD; including amputations and dysmelia; *n*=18), visual or hearing impairments (VH; *n*=7) and other disabilities (including degenerative neurological muscle diseases (*n*=3), hip impairments (*n*=3), nerve damage in the lower body (*n*=2), connective tissue disease (*n*=1), cognitive disorder (*n*=1), rheumatic disease (*n*=1) and complex regional pain syndrome (*n*=1); *n*=12). One participant was unable to undergo the DXA measurement, and as a result of the lack of body composition data, this participant was excluded from the regression analysis.

The characteristics of the participants are described in Table 3.2. The cohort predominantly consisted of White individuals, with the exception of one Arab-White athlete and two athletes of Latino ethnicity. The groups with different disabilities, did not significantly differ in terms of anthropometrics, except for a lower FFM in a athletes with SCD compared with VH athletes (P=0.015). None of the athletes displayed clinically abnormal total T3 concentrations.

Measured resting metabolic rate

The measured RMR was 1386±258 kcal/day for females and 1686±302 kcal/day for males. As shown in Table 3.2, a significant difference in RMR was observed between the SCD (1366±241 kcal/day) and VH group (1744±347 kcal/day; P=0.046). The groups of athletes with a neurological condition (1581±316kcal/day), limb deficiency (1512±268 kcal/day), or 'other disability' (1646±379 kcal/day) did not differ significantly from any other group. When expressed relative to FFM, there were no differences in RMR between sexes or between the groups with different disabilities.

Table 3.3. Backward stepwise multiple regression models with measured resting metabolic rate as outcome variable.

Outcome variable: Measured resting metabolic rate	Unstandardized Coefficients		Standardized Coefficients			
	B	Std. Error	Beta (β)	t	R^2_{adj}	*P*-value
Model					0.712	**<0.001**
(constant)	103.191	159.644		0.646		0.521
Fat-free mass	**23.310**	**2.197**	0.781	10.610		**<0.001**
Triiodothyronine (T3)	**200.897**	**68.842**	0.203	2.918		**0.005**
Spinal cord disorder	**-108.361**	**49.786**	-0.160	-2.177		**0.034**
Outcome variable: Measured resting metabolic rate	**Unstandardized Coefficients**		**Standardized Coefficients**			
	B	Std. Error	Beta (β)	t	R^2_{adj}	*P*-value
Model					0.659	**<0.001**
(constant)	428.831	119.083		3.601		**<0.001**
Fat-free mass	22.770	2.261	0.762	10.073		**<0.001**
Spinal cord disorder	**-101.811**	**50.850**	-0.151	-2.002		**0.050**
Outcome variable: Measured resting metabolic rate	**Unstandardized Coefficients**		**Standardized Coefficients**			
	B	Std. Error	Beta (β)	t	R^2_{adj}	*P*-value
Model					0.657	**<0.001**
(constant)	489.520	124.649		3.927		**<0.001**
Body mass	14.885	1.835	0.621	8.113		**<0.001**
Spinal cord disorder	**-119.649**	**49.337**	-0.180	-2.425		**0.018**
Male	**195.999**	**46.745**	0.312	4.193		**<0.001**

Regression analyses

To explore potential predictors of RMR in Paralympic athletes, a multiple linear regression with backward selection was initially conducted, with RMR being treated as the dependent variable, while FFM, height, total T3 concentrations, presence of spasms, and the presence of SCD were included as potential predictors. The final regression model (Table 3.3) contained FFM, total T3 concentrations, and the presence of SCD as predictors ($F(3,57) = 50.3$, $P<0.001$, adjusted $R^2=0.71$). All retained variables

were statistically significant in the final regression model, $P<0.05$. Based on this regression analysis the following prediction equation can be formulated.

Equation 1:

$$RMR = 103.191 + (23.310 * FFM) + (200.897 * T3) - (108.361 * SCD)$$

Here, RMR is expressed in kcal/day, FFM in kg, T3 in nmol/L, and SCD is binary (1 for presence, 0 for absence).

As serum T3 concentrations are not always available in daily practice, the regression analysis was rerun without considering T3 as a potential predictor. The resulting regression model included FFM and the presence of SCD as predictors ($F(2,63)=63.742$, $P<0.001$, adjusted $R^2=0.66$). Both retained variables were statistically significant in the final regression model, $P<0.05$. Based on this regression analysis the following prediction equation can be formulated.

Equation 2:

$$RMR = 428.831 + (22.770 * FFM) - (101.811 * SCD)$$

Here, RMR is expressed in kcal/day, FFM in kg, and SCD is binary (1 for presence, 0 for absence).

If FFM is not available, an alternative approach would be to use body mass and sex instead of FFM. The resulting regression model included body mass, sex, and the presence of SCD ($F(3,63)=43.214$, $P<0.001$, adjusted $R^2=0.66$). All retained variables were statistically significant in the final regression model, $P<0.05$. Based on this regression analysis the following prediction equation can be formulated.

Equation 3:

$$RMR = 489.520 + (14.885 * \text{body mass}) - (119.649 * SCD) + (195.999 * \text{sex})$$

Here, RMR is expressed in kcal/day, body mass is in kg, SCD is binary (1 for presence, 0 for absence), and sex is binary (1 for male, 0 for female).

Table 3.4. Comparisons between prediction equations and the measured resting metabolic rate.

	RMR	Accurate		Over prediction		Under prediction		RMSE	ICC
	(kcal/day)	*n*	%	*n*	%	*n*	%	kcal	
Measured	1520 ± 315								
Equation 1	1517 ± 259	46	70	9	14	11	17	141	0.804
Equation 2	1517 ± 258	45	68	10	15	11	17	137	0.802
Equation 3	1521 ± 258	44	66	11	16	12	18	136	0.805
Chun[18]	1450 ± 259	42	63	9	13	16	24	141	0.789
Nightingale[19]	1449 ± 248	41	61	9	13	17	25	141	0.782
Schofield[38]	1499 ± 204	41	61	13	19	13	19	160	0.708
WHO[39]	1555 ± 250	40	60	17	25	10	15	157	0.764
Cunningham[31]	1583 ± 232	40	61	19	29	7	11	163	0.769
Harris-Benedict[32]	1546 ± 254	38	57	18	27	11	16	158	0.774
Roza-Shizgal[33]	1534 ± 254	37	55	16	24	14	21	157	0.767
Owen[37]	1447 ± 245	37	55	11	16	19	28	172	0.720
Mifflin[36]	1470 ± 269	35	52	14	21	18	27	174	0.733
Spijker-Hoven[34]	1651 ± 300	27	40	34	51	6	9	217	0.750
Ten Haaf[35]	1650 ± 302	26	39	34	47	7	10	208	0.761
De Lorenzo[40]	1678 ± 309	19	28	39	58	9	13	278	0.575

RMR = resting metabolic rate. RMSE = root-mean square error. ICC = intraclass correlation coefficient. Accurate is within 10% of the measured RMR, over- or underprediction is at least 10% higher or lower, respectively, than measured resting metabolic rate.

Predicted vs measured RMR

Table 3.4 presents the results regarding the accuracy of the predicted vs measured RMR. Prediction Equation 1 showed the highest accuracy, with 70% of the athletes having their RMR predicted within 10% of the measured RMR. As shown in Figure 3.2, athletes with a low RMR were more likely to have an overprediction of their RMR, while athletes with a high RMR were more likely to have an underprediction of their RMR. Among the pre-existing prediction equations, Chun's (18) and Nightingale & Gorgey's (19) equation showed a high accuracy (63 and 61%, respectively), accompanied by relatively low RMSE values of 141 kcal/day for both equations and high ICC of 0.789 and 0.782, respectively. Considering prediction equations that do not use FFM, prediction Equation 3 showed a high accuracy (66%), along with a RMSE of 136 kcal/day and

ICC of 0.805. Furthermore, the WHO equation (39), which incorporates sex, age, body mass, and height, performed relatively well, achieving an accuracy of 60%, an RMSE of 157 kcal/day, and ICC of 0.764. Consistent with the accuracy findings, novel prediction Equations (1, 2 and 3) as well as the pre-existing prediction equations of Chun(18), Nightingale & Gorgey(19), and WHO(39) also showed relatively low bias (0, 0, 0, -67, -68 and 35 kcal, respectively) with acceptable limits of agreement, as evidenced by the Bland Altman plots (Figure 3.3). Interestingly, the three pre-existing prediction equations specifically formulated for athletes, i.e. Spijker-Hoven(34), Ten Haaf (35), and De Lorenzo(40), demonstrated poor performance, with accuracies ≤40%, and RMSE values >200 kcal/day. Bland-Altman analyses supported these findings, showing large positive bias for these three equations, indicating substantial overprediction of RMR in Paralympic athletes.

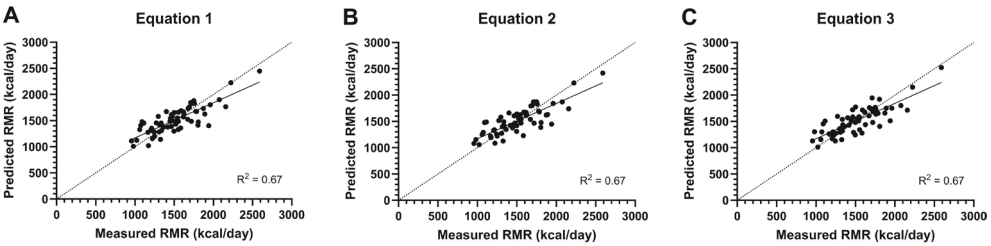

Figure 3.2 Predicted vs measured resting metabolic rate (RMR). RMR was predicted according to three prediction equations, i.e. with prediction factors fat-free mass (FFM), total triiodothyronine and the presence of spinal cord disorder (SCD) (panel A; Equation 1), RMR predicted from FFM and the presence of SCD (panel B; Equation 2), RMR predicted from body mass, sex and the presence of SCD (panel C; Equation 3). The solid line represents the linear regression line of the prediction equations, with the corresponding R^2. The dashed line is the regression line through origin with a slope of 1.

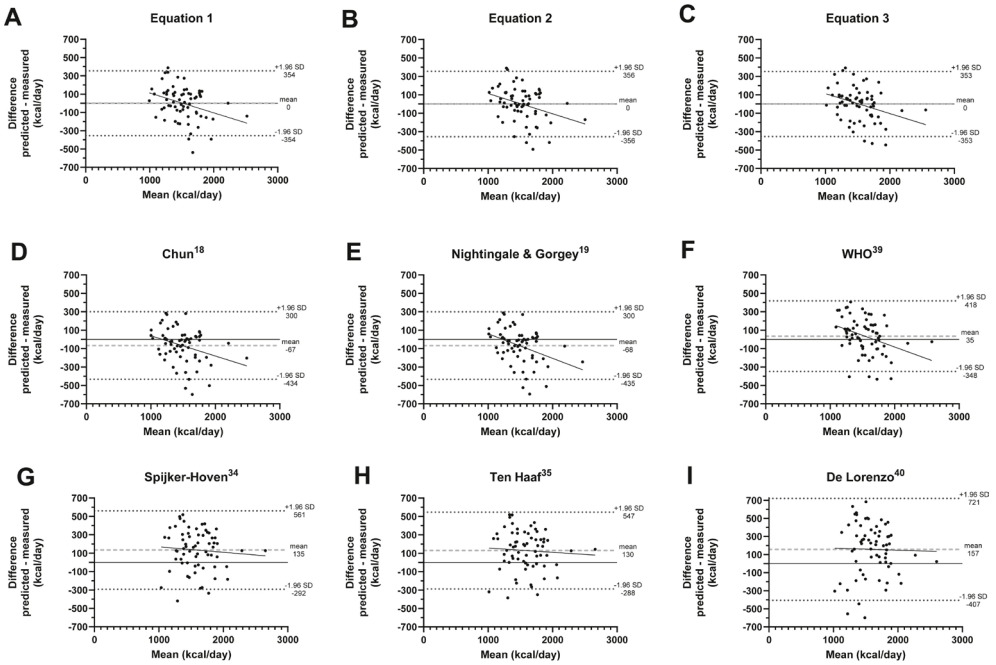

Figure 3.3 Bland–Altman plots of predicted vs measured resting metabolic rate (RMR) of Dutch and Norwegian Paralympic athletes. Panels A, B, and C represent the novel prediction equations (Equations 1, 2, and 3 respectively), panels D through I represent pre-existing prediction equations.18,19,34,35,39,40 The black dotted horizontal lines represent the 95% limits of agreement, and gray dashed horizontal lines represents the bias between predicted and measured RMR.

DISCUSSION

The measured RMR was 1386±258 kcal/day and 1686±302 kcal/day for females and males respectively, showing a wide range from 995 to 2589 kcal/day. Most of the variation in RMR between individuals and sex can be explained by differences in FFM. Furthermore, the presence of SCD has a negative impact on RMR, while other disabilities did not appear to influence RMR. In addition to FFM and SCD, also serum total T3 concentration explained some of the variation in RMR. Notably, the newly derived prediction equations based on the current data, as well as the pre-existing prediction equations developed by Chun and colleagues(18) and Nightingale and Gorgey,(19) demonstrated the highest accuracy to predict RMR in Paralympic athletes.

So far, studies assessing RMR in disabled athletes were conducted with small sample sizes, specific disabilities(41) or specific sports.(17, 20, 42) In the current study, the RMR was measured in a large population of Paralympic athletes, including various disabilities and sports. The mean RMR of 1520 kcal/day (31.1 kcal/kg FFM/day) was in line with the mean RMR previously reported in Para swimmers (1459 kcal/day)(17) and wheelchair racers and hand bikers (1521 kcal/day).(42) However, the RMR of wheelchair rugby players (1735 kcal/day) was considerably higher compared to the current findings, even when expressed relative to FFM (37 kcal/kg FFM).(20) These apparent differences in RMR values between studies are likely explained by different instruments or protocols to measure or analyze RMR and FFM, thereby potentially introducing systematic bias.

The regression analyses identified FFM as the primary predictor of RMR, which is in line with previous literature on RMR in a population without disabilities.(5) Notably, while the mean absolute RMR values showed considerable variation between groups with different disabilities, these differences disappeared when expressing RMR relative to FFM. FFM consists of various components like bones, skin, muscles and vital organs such as the brain, kidneys, liver, and heart, each with its own metabolic rate.(43) Even though the vital organs make up a small fraction of the FFM, they are responsible for 70–80% of the RMR.(44) Therefore, it can be argued that differences in FFM due to limb deficiencies or nerve denervation, which primarily affect muscle mass and not organ mass, did not result in a difference in RMR per kg FFM.

While both FFM and serum total T3 concentrations showed a positive relationship with RMR, the presence of SCD had a negative impact on RMR. Some studies completely attributed the lower RMR in individuals with SCI to lower FFM.(45, 46) However, Monroe et al.(47) and Polfuss et al.(48) reported a lower RMR in individuals with SCI and spina bifida, respectively, even after correcting for FFM. The latter findings are in line with the results in this study, as the presence of a SCD negatively affected RMR, independent from FFM. A possible explanation is that the presence of SCD leads to a disconnection between the brain and the peripheral SNS. This can lead to a decreased SNS activation,(9) and subsequent decrease in RMR. Indeed, studies have demonstrated that pharmacological inhibition of the SNS can lead to a 4 to 9% decrease in RMR.(49–51) This decrease is consistent with the findings of this study, as the presence of SCD was associated with a ~103 kcal (~6%) lower RMR.

Besides alterations in SNS activity, previous literature suggested that individuals with SCD can also suffer from hypothyroidism.(11) This was not confirmed by the current study, as none of the athletes in the cohort displayed clinically low or high total T3 levels. Nevertheless, even within the 'normal' range, serum total T3 concentrations contributed to the prediction of RMR. Indeed, thyroid hormones are known to influence metabolic rate, with higher concentrations associated with increased RMR.(52) Although the exact mechanisms are not yet fully understood, it is thought that thyroid hormones increase the metabolic rate by increasing the adenosine triphosphate (ATP) production and by maintaining and generating ion gradients, specifically the NA^{+}/K^{+} gradient across cell membranes(53) and the Ca^{2+} gradient between the cytoplasm and the sarcoplasmic reticulum.(54) Thyroid hormones also increase the uncoupling oxidative phosphorylation in mitochondria,(55) leading to an increase in energy expenditure in the form of heat.

In terms of predictive accuracy, the newly developed prediction equations demonstrated high accuracy, with up to 70% of the athletes having their RMR predicted within 10% of their measured RMR. Aditionally, the equations displayed a low RMSE ranging from 136 to 141 kcal, along with satisfactory limits of agreement. As such, the predictive accuracy of these new equations is higher than most of the prediction equations recently evaluated for athletes without disabilities.(3) These findings are promising, suggesting that these newly developed equations hold potential as tools for estimating RMR in Paralympic athletes. It is important to acknowledge, however, that the evaluation of the accuracy was conducted with the same cohort of athletes, whose characteristics were used for the initial regression analyses, which might have inflated the predictive accuracy.(4) Nevertheless, given the diversity of the cohort of this study (e.g. females and males, various disabilities, various sports), we believe that the new prediction equations will be accurate in other cohorts of Paralympic athletes. Among the pre-existing prediction equations, the equations of Chun and colleagues(18) and Nightingale & Gorgey(19) were also found to be accurate. While these equations were initially developed for non-athletes with SCI, they demonstrate good predictive accuracy when applied in the current, more diverse cohort of Paralympic athletes, comprising a large variety of disabilities. This finding supports their broad applicability within the context of Paralympic athletes. In contrast, some of the preexisting prediction equations specifically developed for athletes, such as those by Spijker-Hoven(34), Ten Haaf(35), and De Lorenzo(40), demonstrated the weakest performance in the current cohort

of Paralympic athletes. Interestingly, the RMR prediction equation of Ten Haaf(35) and De Lorenzo(40) have recently been identified as the most accurate prediction equations for athletes without disabilities according to two meta-analyses.(3, 4) The common denominator in the latter prediction equations is the strong emphasis on body height, which does not seem to be an appropriate predictor of RMR in Paralympic athletes. This can be explained by the physical characteristics of Paralympic athletes, such as limb deficiencies or muscle atrophy, that may alter the ratio between body height, body mass, and FFM. This further emphasizes the importance of prediction equations specifically developed for Paralympic athletes.

Practical implications

The newly developed RMR prediction Equation 1, encompassing FFM, total T3 and the presence of SCD, demonstrated the highest accuracy for estimating the RMR. As serum total T3 concentrations might not always be readily available, this equation may be less suitable in daily practice. The predictive accuracy of Equation 2, which includes FFM and the presence of SCD as predictors of RMR, is only marginally lower compared to Equation 1, making it a viable alternative. Moreover, when FFM is replaced by body mass and sex (Equation 3), the accuracy outcomes are largely similar to Equation 2. Therefore, this approach (Equation 3) offers a valuable solution to predict RMR in situations where FFM data are unavailable. It can even be argued that the greater availability and accuracy of body mass as opposed to FFM measurements, favors the use of body mass and sex (Equation 3) over FFM (Equation 2) to predict RMR.

Strengths and limitations

The strength of the current study is the comprehensive assessment of the RMR and its potential predictors in a cohort of Paralympic athletes competing in various sport, and comprising diverse disabilities. However, we should also acknowledge some limitations. Due to the international nature of the study, RMR was assessed at two different research sites using two different ventilated hood systems, while FFM was assessed using three different DXA systems. Although this might increase variability in RMR and FFM, operating procedures were standardized across research sites, thereby minimizing potential measurement errors. Nonetheless, it is important to acknowledge that bias may have been introduced due to the use of multiple devices. This potential bias could have impacted the strength of the observed associations. Furthermore, it is conceivable that in instances where certain disabilities or factors exert only a minor in-

fluence on RMR, this effect might have been overlooked due to variation induced by bias. Conversely, the employment of multiple devices could enhance the external validity of the study, as the prediction equations are not reliant on the idiosyncrasies of a single device.

Although the cohort was highly diverse, with both men and women and various disabilities, the cohort mainly contained individuals of White ethnicity. In this regard, White individuals are recognized to typically exhibit a higher RMR compared with some other ethnicities.(56–58) It has been suggested that these differences might be due to differences in organ mass. For practical application of the novel equations, this factor should be considered when assessing the RMR of athletes with various ethnicities.

CONCLUSION

In conclusion, FFM, T3 concentration and the presence of SCD are the main predictors of RMR in Paralympic athletes, accounting for 71% of the variance in measured RMR. Spasticity and other disabilities do not appear to affect RMR in this cohort. The novel prediction equations derived from this study, as well as the pre-existing equations of both Chun and colleagues and Nightingale and Gorgey, showed good agreement with the measured RMR and should, therefore, be considered as the preferred prediction equations to estimate RMR of Paralympic athletes.

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Chapter 4

Feasibility and Accuracy of Body Fat Assessment using Standardised Skinfold Thickness Assessment versus Dual-Energy X-ray Absorptiometry in Paralympic Athletes

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ABSTRACT

Purpose: To evaluate the feasibility and accuracy of body fat assessment using standardised skinfold thickness assessment versus dual-energy x-ray absorptiometry (DXA) in Paralympic athletes.

Method: In this cross-sectional study, body composition was assessed in 49 male and female Paralympic athletes (Para cycling, skiing, swimming, wheelchair basketball, wheelchair tennis) by a whole-body DXA scan and skinfold thickness measurements conducted according to International Society for the Advancement of Kinanthropometry (ISAK) standards. Correlation and Bland-Altman analyses were conducted to compare both methods.

Results: DXA was feasible in all athletes, while the sums of 4, 7, and 8 skinfolds were obtained in 88%, 73%, and 73% of the athletes, respectively. Median DXA-derived body fat percentage was 16.3% (13.4 – 20.5%) in males and 27.8% (21.1 – 33.4%) in females. Strong correlations were found between DXA-derived body fat percentage and the sum of 4 ($r = .85$), 7 ($r = .83$), and 8 ($r = .83$) skinfolds. However, skinfold-based prediction equations for estimating body fat percentage were associated with substantial negative bias (-2.0% to -7.9%) and large individual error compared with DXA.

Conclusion: DXA is a feasible method for assessing body composition in Paralympic athletes, while ISAK skinfold measurements face some challenges due to disability-related landmarking issues. Despite these limitations, skinfold thickness remains strongly associated with DXA-derived body fat. It is recommended to measure all skinfolds that can be reliably obtained according to ISAK standards and interpret them as a cumulative 'sum of feasible sites', rather than enforcing a universal skinfold metric across all Paralympic athletes.

INTRODUCTION

The assessment and analysis of body composition has become a fundamental part of evaluating athletes' health status and is considered a key factor in optimising sports performance [1]. While body composition in many sports disciplines and across different competitive levels is well-documented, limited research exists on the body composition of athletes with an impairment. The body composition of these athletes likely differs substantially from non-disabled athletes due to factors such as limb loss, muscle atrophy, and short stature. Additionally, ambulation differences, distinct physical activity patterns, and specific sports may also contribute to differences in body composition [2]. A better understanding of the body composition of athletes with an impairment, along with appropriate methods to assess body composition in this population, is needed to further optimise their health and sports performance.

Dual-energy X-ray absorptiometry (DXA) is commonly used as preferred method for assessing body composition in athletes due to its high precision, reproducibility, and ability to provide both whole-body and regional estimates of fat, lean and bone tissue [3,4]. Although DXA is not considered the absolute gold standard, such as a four-compartment model, its strong agreement with multi-compartment models [5], low burden, and widespread use in research support its role as a practical reference method in both clinical and sports science contexts. Despite its increasing availability, DXA is still not widely accessible for sports physicians or sports nutritionists in their daily practice. Consequently, skinfold thickness assessment is one of the most commonly used methods to assess body composition. This technique involves the use of a calliper to measure a double layer of gripped skin and underlying subcutaneous fat tissue at various body sites to establish an overall measurement of subcutaneous adiposity [6]. In non-disabled athletes, the sum of skinfolds obtained by strictly standardised skinfold thickness assessment shows a high correlation and level of agreement with whole-body fat mass obtained from DXA [7-10]. Thus, when conducted according to strict standardisation procedures, such as those by the International Society for the Advancement of Kinanthropometry (ISAK) [11], skinfold thickness assessment can serve as a valid alternative to DXA [6]. Nevertheless, assessing skinfold thickness in athletes with an impairment presents unique challenges due to factors such as amputations, muscle atrophy, limb deficiencies, or combinations thereof. Given these complexities, there is a need to evaluate both the

feasibility and accuracy of ISAK skinfold thickness assessment to assess body composition in the population of athletes with an impairment.

The aim of this study was to examine the body composition of Paralympic athletes and to critically evaluate the feasibility and accuracy of ISAK skinfold thickness assessment for estimating body fat compared with DXA. Although the ISAK skinfold thickness assessment may encounter additional feasibility challenges in Paralympic athletes, we hypothesized that it will still accurately reflect body fat in this population.

METHODS

Study design

In this cross-sectional study, body composition was assessed both by DXA and skinfold thickness assessment in Dutch Paralympic athletes. Data were collected between September 2020 and September 2022 at the (mobile) sport and research centre of HAN University of Applied Sciences, the Netherlands. Before data collection, participants were informed of the nature and potential risks of the study, after which written consent was obtained. This study was approved by the Medical Ethical Committee Zuyd, the Netherlands (NL72682.096.20), and adhered to the standards for the use of human participants as outlined in the Declaration of Helsinki [12]. The current study was part of a greater project on the nutritional requirements in a cohort of Paralympic athletes [13–15]. In the current study, a subpopulation of 49 Dutch Paralympic athletes were included from whom body composition measurements were obtained by DXA and ISAK skinfold thickness assessment.

Participants

A total of 49 male (n=25) and female (n=24) Paralympic athletes were included in current analysis. Participants competing at the highest (inter)national level were recruited through ongoing partnerships between HAN University of Applied Sciences and the Dutch Olympic/Paralympic committee and national sport federations. Paralympic athletes participating in Para cycling, wheelchair basketball, wheelchair tennis, Para skiing, and Para swimming were approached to participate. Exclusion criteria were pregnancy or an injury that disrupted their regular training regimen. The athletes were categorized as being wheelchair users if more than 50% of their ambulatory activities outside sports were performed in a wheelchair.

Study procedures

Participants arrived at our (mobile) laboratory by car or public transport between 7:30 – 9:00 AM. All athletes arrived in the morning after an overnight fast and had refrained from strenuous exercise, sauna use, or alcohol consumption for at least 24 hours prior to measurement. First, body mass and stature were determined, followed by DXA scanning procedures and skinfold thickness assessment.

Measurements

Dual X-ray absorptiometry

After voiding, the body mass and stretch stature were determined using a digital scale and mobile stadiometer, respectively (Seca 770 and 213i, Hamburg, Germany). If participants were unable to stand upright due to their disability, the stretch stature was measured in supine position from heel to the top of the head with a tape measure. Body composition was assessed using whole-body DXA scans performed on one of two cross-calibrated systems (Hologic Horizon or Hologic Discovery A; Hologic, MA, USA). One scanner was located in the laboratory, whereas the other was mounted in a trailer that could be transported to the participants' training locations. Whole-body composition and regional body composition were determined with the participants positioned according to NHANES procedures [16]. If possible, a foot strap was used to secure the feet and maintain the legs in slight internal rotation. If the procedures could not be followed due to a disability, participants were placed in a position they could maintain for the duration of the scan. Minor metal implants were manually excluded using DXA software and the adjusted scans were subsequently included in the analyses. Body composition analyses were conducted using the system's software package (Hologic Horizon: Apex version 5.6.0.5, Hologic Discovery A: Apex version 4.5.3) without NHANES correction. In the morning before measurements took place, the DXA system was calibrated according to the manufacturer's instructions.

Anthropometrics

Anthropometric measurements were taken following guidelines of the International Society for the Advancement of Kinanthropometry [11]. Skinfolds were assessed on the right side of the body and included 8 skinfolds (triceps, subscapular, biceps, iliac crest, supraspinale, abdominal, front thigh and medial calf). Skinfold thicknesses were measured with Harpenden skinfold callipers (Baty International, Burgess Hill, England). Each measurement was taken twice by an ISAK-accredited anthropometrist

(levels 1–3). If the two measurements exceeded a 5% error, a third was taken, and the mean of two or median of three was used for subsequent analysis. The sums of 4, 7, and 8 skinfolds were computed: 8 includes all sites; 7 excludes the iliac crest; and 4 includes triceps, subscapular, biceps, and iliac crest. To further analyse segmental body composition, the sum of skinfolds at the right arm: triceps and biceps, trunk: subscapular, iliac crest, supraspinale and abdominal, and right leg: front thigh and medial calf, were conducted. In addition to skinfolds, girth measurements (arm relaxed, arm flexed and tensed, waist, hip, calf) were conducted with a flexible steel tape according to ISAK protocol. Each site was measured twice, with a third taken if values differed by more than 1%, and the mean or median used for analysis. Corrected girths of the arm and calf were calculated by subtracting $\pi \times$ skinfold thickness from the raw circumference [11]. Given the measurement complexities associated with certain disabilities, the ISAK protocol was adapted when necessary: (i) if a skinfold site or girth could not be obtained on the right side due to amputation or deformity, the measurement was taken on the left side; (ii) if the participant was unable to stand upright, stretch stature was measured in the supine position from heel to head using a measuring tape; (iii) if the participant had bilateral limb loss or abnormalities (e.g., bilateral hip dislocation), no measurements were taken at the affected sites; and (iv) if a standing waist girth measurement was not possible, it was taken in the seated position, whereas the hip girth could not be obtained in this situation. Intra-tester technical error of measurements (TEMs) were <1.2% for all individual skinfolds, except for the front thigh skinfold (5.8%). Girth measurements yielded consistently low TEMs (<1%).

Five skinfold-based prediction equations for estimating body fat percentage were used for both males and females: Durnin & Womersley [17], Evans et al. [18], Wilmore & Behnke [19], Yuhasz [20], and Withers [21,22]. These particular equations were selected because they are available for both males and females, and use skinfold thickness sites included in the ISAK protocol. The Yuhasz equation directly estimates body fat percentage based on skinfold thickness, whereas the other prediction equations estimate body density. The body density derived from these equations was converted to body fat percentage using the Siri equation [23].

Statistical analysis

Statistical analyses were performed using SPSS 27.0 (IBM Corp., Armonk, NY), with statistical significance set at $P<0.05$. Normality of the

descriptive statistics was tested using the Shapiro-Wilk test. Normally distributed data were presented as mean ± SD, while non-normally distributed data were presented as median with interquartile range. Differences between wheelchair and non-wheelchair users were analysed either by an independent samples t-test (for normally distributed data) or by a Mann-Whitney U-test (for non-normally distributed data). Either Pearson's correlation coefficient (for normally distributed data) or Spearman's correlation coefficient (for non-normally distributed data) was calculated between the DXA-derived whole body fat percentage, the sum of 4, 7, 8 skinfolds, and skinfold-based prediction equations for body fat percentage. These correlation coefficients were also used to assess the relation between DXA-derived regional fat percentages at the trunk, right arm, and right leg, and the sum of skinfolds of the right arm, trunk, and right leg. Correlation coefficients were further computed between DXA-derived regional lean and fat mass and both corrected and uncorrected girths. The strength of correlations was defined as very weak, r: 0 – 0.19, weak, r: 0.2 – 0.39, moderate, r: 0.4 – 0.59, strong, r: 0.6 – 0.79, very strong r: 0.8 – 1.0 [24]. Bland-Altman analyses were performed using GraphPad Prism (Version 10.4.1) to assess the agreement between body fat percentage derived from DXA and that estimated using skinfold-based prediction equations.

RESULTS

Participants' characteristics

A total of 49 (51% male) Paralympic athletes (27.5 ± 9.0 y) participated. The athletes competed in various sports disciplines, including Para cycling (*n*=17), wheelchair basketball (*n*=12), wheelchair tennis (*n*=9), Para skiing (*n*=7), and Para swimming (*n*=4). The participants were diagnosed with a spinal cord disorder (spina bifida, traumatic and non-traumatic spinal cord injury ranging from T4 to L3 complete and incomplete lesions; *n*=15), neurological disorder (including cerebral palsy and other neurological disorders; *n*=5), limb loss (including dysmelia and amputations; *n*=20), visual impairment (*n*=4), or other disabilities (e.g. rheumatism, intellectual disability, Perthes disease) (*n*=5). In total, 51% of the participants were categorized as wheelchair users.

Feasibility of body composition assessment

DXA measurements were successfully completed in all participants. As for the ISAK skinfold thickness assessment, the sum of 4, 7 and 8 skinfolds

could be calculated for 88, 73, and 73% of the participants, respectively. Triceps, subscapular, and biceps skinfolds were successfully completed in 98 to 100% of the cases. The iliac crest, supraspinale, abdominal, front thigh and medial calf could be obtained in 90, 88, 92, 82, and 78% of the cases, respectively. Girths were obtained in 82 to 100% of the cases, with the exception of the hip girth (59%)(Table 4.1).

Table 4.1 Feasibility of DXA and skinfold thickness assessment outcomes

	Success rate, n/49 (%)
Basic measurements	
Body mass	49/49 (100)
Standing stretch stature	39/49 (80)
DXA-derived measurements	
Body fat mass	49/49 (100)
Lean tissue mass	49/49 (100)
Body fat percentage	49/49 (100)
Skinfold-derived measurements	
Triceps skinfold	48/49 (98)
Subscapular skinfold	49/49 (100)
Biceps skinfold	48/49 (98)
Iliac crest skinfold	44/49 (90)
Supraspinale skinfold	43/49 (88)
Abdominal skinfold	45/49 (92)
Front thigh skinfold	40/49 (82)
Medial calf skinfold	38/49 (78)
Σ4 skinfolds	43/49 (88)
Σ7 skinfolds	36/49 (73)
Σ8 skinfolds	36/49 (73)
Girths	
Waist girth	46/49 (94)
Hip girth	29/49 (59)
Arm girth relaxed	49/49 (100)
Arm girth flexed and tensed	49/49 (100)
Corrected arm girth	48/49 (98)

Table 4.1 Feasibility of DXA and skinfold thickness assessment outcomes (*continued*)

	Success rate, n/49 (%)
Calf girth	40/49 (82)
Corrected calf girth	38/49 (78)

Data presents the assessment percentages, which indicate the proportion of valid assessments out of the total number of assessments (n=49) for each measurement. Σ: indication of summation. Σ4 skinfolds includes measurements from the triceps, subscapular, biceps and iliac crest skinfold sites. Σ7 skinfolds includes measurements from all skinfold sites according to ISAK, except for the iliac crest. Σ8 skinfolds includes measurements from all skinfold sites according to ISAK.

Body composition of Paralympic athletes

Table 2 presents the results of assessment of body composition by both DXA and ISAK assessment. DXA-derived body fat percentage was 16.3% (13.4 – 20.5%) for males and 27.8% (21.1 – 33.4%) for females. Moreover, DXA-derived body fat percentage in male wheelchair users 17.8% (15.9 – 21.8) was higher compared to male non-wheelchair users (13.7% (11.4 – 18.3%)). No significant differences in DXA-derived body fat percentage were observed between female wheelchair and non-wheelchair users (32.5% (21.2 – 34.5%) versus 25.1% (20.6 – 30.1%), respectively). With regard to ISAK skinfold thickness assessment, females displayed higher values at all measured sites compared to males, resulting in a greater sum of 4, 7 and 8 skinfolds in females. Median girth measurements were consistently higher in males across all sites than females (Table 4.2).

Body fat percentages estimated by skinfold-based prediction equations were consistently lower than those derived from DXA (Table 2). Specifically, estimated body fat percentages ranged from 8.3% (7.5 – 12.5%) to 12.4% (9.7 – 18.0%) in males, depending on the skinfold-based prediction equations used, while for female the range was 17.2% (13.1 – 23.1%) to 27.5% (19.4 – 33.0%).

Correlations between DXA and skinfold-based outcomes of body fat

Very strong significant correlations were observed between DXA-derived body fat percentage and the sum of 4 skinfolds (r=.85), sum of 7 skinfolds (r=.83), and sum of 8 skinfolds (r=.83) when assessed over all participants (Figure 4.1A – C). However, when analysing males and females separately, correlations remained strong for males, but became

Table 4.2. Body composition outcomes of DXA and ISAK measurements (*n*=49).

	Male			Female		
	Total (n=25#)	Wheelchair (n=12#)	Non-wheel-chair (n=13#)	Total (n=24#)	Wheelchair (n=13#)	Non-wheel-chair (n=11#)
Anthropometrics						
Body mass (kg)	70.5 (64.6 – 74.9)	64.6 (61.5 – 67.6)	72.1 (70.6 – 91.6)*	60.4 (54.1 – 68.2)	57.9 (52.0 – 65.9)	61.9 (55.7 – 72.5)
Stretch stature (m)	180.3 (168.0 – 192.4)	166.5 (153.3 – 188.1)	182.9 (178.4 – 193.4)	168.7 (164.5 – 171.1)	167.9 (157.6 – 172.0)	169.9 (168.1 – 171.2)
Body Mass Index (kg/m2)	22.1 (20.0 –27.7)	20.9 (19.1 – 30.9)	22.4 (20.0 – 26.9)	21.1 (19.1 – 24.1)	20.7 (19.5 – 23.4)	21.7 (18.9 – 25.7)
DXA-derived body composition						
Body Lean mass (kg)	55.1 (49.0 – 59.6)	49.0 (41.9 – 52.7)	59.4 (57.3 – 68.1)*	42.3 (36.9 – 47.0)	38.8 (34.6 – 43.2)	46.6 (41.7 – 50.3)*
Body fat mass (kg)	10.2 (8.3 – 15.9)	11.6 (8.9 – 14.9)	9.6 (7.9 – 18.0)	17.0 (12.3 – 21.9)	18.4 (10.7 – 23.2)	14.3 (12.3 – 19.6)
Body fat percentage (%)	16.3 (13.4 – 20.5)	17.8 (15.9 – 21.8)	13.7 (11.4 – 18.3)*	27.8 (21.1 – 33.4)	32.5 (21.2 – 34.5)	25.1 (20.6 – 30.1)
Right arm lean mass (kg)	4.5 (3.3 – 5.3)	4.6 (3.3 – 5.3)	4.4 (3.2 – 5.7)	2.8 (2.4 – 3.1)	2.9 (2.7 – 3.3)	2.5 (2.2 – 3.0)*
Right arm fat mass (kg)	0.6 (0.5 – 0.8)	0.7 (0.5 – 0.8)	0.6 (0.5 – 1.0)	1.0 (0.8 – 1.3)	1.1 (0.9 – 1.5)	0.8 (0.8 – 1.2)
Right arm fat percentage (%)	12.7 (9.5 – 14.9)	12.7 (8.8 – 15.2)	12.7 (10.2 – 14.8)	25.7 (22.2 – 33.1)	27.6 (22.4 – 33.8)	25.1 (19.7 – 31.4)
Trunk lean mass (kg)	29.0 (26.4 – 32.9)	26.5 (24.4 – 30.3)	31.2 (28.3 – 35.3)*	22.2 (20.5 – 24.1)	21.2 (19.9 – 24.1)	23.4 (21.5 – 24.1)
Trunk fat mass (kg)	4.5 (3.8 – 7.0)	5.5 (3.9 – 6.0)	4.1 (3.7 – 8.6)	7.1 (4.6 – 9.2)	7.2 (4.7 – 9.3)	5.8 (4.2 – 7.8)

Table 4.2. Body composition outcomes of DXA and ISAK measurements (*n=49*). (*continued*)

	Male			Female		
Trunk fat percentage (%)	13.7 (11.5 – 17.2)	15.4 (12.4 – 17.1)	11.7 (10.5 – 17.5)	23.8 (16.3 – 29.6)	25.1 (17.9 – 32.4)	20.6 (14.4 – 24.3)
Right leg lean mass (kg)	5.7 (3.5 – 9.8)	4.1 (3.2 – 5.1)	9.6 (8.5 – 10.7)*	4.2 (3.2 – 7.2)	3.6 (2.8 – 4.8)	7.3 (4.1 – 8.1)*
Right leg fat mass (kg)	2.1 (1.3 – 2.8)	2.3 (1.1 – 3.3)	1.9 (1.4 – 2.6)	3.1 (2.0 – 4.4)	3.4 (2.0 – 4.6)	3.1 (2.0 – 4.4)
Right leg fat percentage (%)	24.0 (16.3 – 33.6)	31.8 (24.4 – 40.7)	16.3 (13.3 – 24.5)*	38.8 (28.7 – 49.6)	43.4 (34.0 – 56.1)	33.6 (27.7 – 41.2)
Sum of skinfolds						
Σright arm (mm)	9.9 (8.6 – 13.6)	12.3 (9.8 – 13.7)	9.7 (6.5 – 16.8)	21.0 (16.2 – 25.5)	21.7 (17.6 – 27.0)	19.7 (16.1 – 24.6)
Σtrunk (mm)	37.6 (24.6 – 65.7)	40.2 (37.6 – 57.9)	28.4 (22.0 – 84.1)	50.8 (37.5 – 68.6)	55.3 (43.8 – 66.5)	41.6 (33.2 – 73.7)
Σright leg (mm)	17.0 (12.5 – 31.0)	29.8 (28.2 – 63.7)	13.5 (10.9 – 23.4)*	36.2 (27.6 – 55.2)	36.9 (30.9 – 59.2)	33.5 (27.0 – 52.7)
Σ4 skinfolds (mm)	28.2 (21.1 – 42.8)	33.9 (28.4 – 40.0)	23.5 (18.2 – 55.6)	45.8 (32.6 – 62.4)	50.3 (37.5 – 73.9)	44.1 (30.0 – 61.1)
Σ7 skinfolds (mm)	42.9 (37.4 – 103.7)	84.6 (68.1 – 138.9)	42.2 (35.3 – 100.3)	92.0 (65.7 – 130.2)	109.5 (68.3 – 134.3)	81.9 (65.7 – 109.6)
Σ8 skinfolds (mm)	50.8 (43.9 – 125.5)	100.3 (80.6 – 168.9)	49.3 (40.6 – 124.8)	107.0 (75.4 – 160.3)	128.9 (75.7 – 160.7)	96.8 (75.4 – 132.9)
Girths						
Waist girth (cm)	78.7 (74.6 – 89.0)	81.0 (73.6 – 89.0)	77.3 (73.6 – 89.7)	72.8 (68.0 – 83.0)	77.4 (71.6 – 84.6)*	69.0 (67.2 – 79.7)*
Hip girth (cm)	94.3 (90.6 – 104.0)	95.2 (93.0 – 97.5)	94.3 (90.5 – 108.3)	93.2 (89.1 – 98.4)	92.9 (87.8 – 97.2)	94.2 (89.6 – 103.1)

Table 4.2. Body composition outcomes of DXA and ISAK measurements (*n=49*). (*continued*)

	Male			Female		
Arm girth relaxed (cm)	34.6 (30.8 – 37.1)	34.9 (30.7 – 36.6)	34.4 (29.6 – 39.4)	30.3 (29.3 – 32.3)	30.9 (29.6 – 34.6)	29.7 (28.0 – 30.9)*
Arm girth flexed and tensed (cm)	36.1 (32.3 – 38.6)	36.8 (33.4 – 38.3)	35.1 (30.6 – 40.4)	31.0 (29.6 – 32.9)	32.4 (30.8 – 33.7)	30.0 (29.4 – 30.9)*
Corrected arm girth (cm)	32.9 (27.1 – 34.3)	32.9 (26.8 – 33.6)	32.3 (28.1 – 34.8)	25.6 (23.8 – 27.8)	27.6 (25.0 – 28.9)	25.3 (23.3 – 25.7)*
Calf girth (cm)	35.0 (29.8 – 38.5)	29.0 (25.0 – 33.0)	38.0 (35.0 – 39.2)*	32.5 (28.2 – 35.8)	30.2 (25.7 – 32.9)	35.0 (31.5 – 38.5)*
Corrected calf girth (cm)	34.0 (25.9 – 36.3)	24.8 (21.4 – 25.9)	35.6 (33.3 – 36.7)*	28.9 (22.6 – 30.4)	22.6 (19.3 – 28.6)	30.3 (28.8 – 32.2)*
Skinfold-derived body fat percentage						
Durnin & Womersley (%)	12.4 (9.7 – 18.0)	15.3 (12.4 – 17.5)	10.8 (7.6 – 20.0)	27.5 (19.4 – 33.0)	28.1 (24.7 – 34.7)	21.1 (17.7 – 30.9)
Evans et al. (%)	9.3 (7.1 – 14.9)	13.8 (10.2 – 14.8)	7.8 (6.9 – 16.8)	21.6 (18.2 – 27.2)	22.1 (16.2 – 28.1)	21.3 (19.6 – 25.1)
Wilmore & Behnke (%)	12.0 (9.8 – 19.6)	14.9 (12.7 – 16.8)	10.0 (9.5 – 20.9)	24.3 (21.6 – 27.9)	26.0 (21.3 – 28.5)	24.2 (22.0 – 25.8)
Yuhasz (%)	8.3 (7.5 – 12.5)	10.0 (8.3 – 12.7)	7.7 (7.0 – 13.7)	17.2 (13.1 – 23.1)	19.6 (13.7 – 23.7)	15.3 (12.9 – 19.6)
Withers (%)	9.6 (7.2 – 21.2)	22.0 (21.0 – 26.5)	9.3 (6.7 – 23.3)	17.9 (13.0 – 23.4)	22.3 (14.3 – 23.9)	16.1 (11.8 – 20.6)

Normal distributed data are presented as mean ± SD, while non-normally distributed data are presented as median (Q1-Q3). Σ: indication of summation. Σright arm: triceps and biceps. Σtrunk: subscapular, iliac crest, supraspinale and abdominal. Σright leg: front thigh and medial calf. Σ4 skinfolds includes measurements from the triceps, subscapular, biceps and iliac crest skinfold sites. Σ7 skinfolds includes measurements from all skinfold sites according to ISAK, except for the iliac crest. Σ8 skinfolds includes measurements from all skinfold sites according to ISAK. * Significantly different ($P<0.05$) compared with wheelchair users of the same sex. # Some outcomes were based on a smaller number of participants, as certain measurements were not feasible for all individuals (see Table 1).

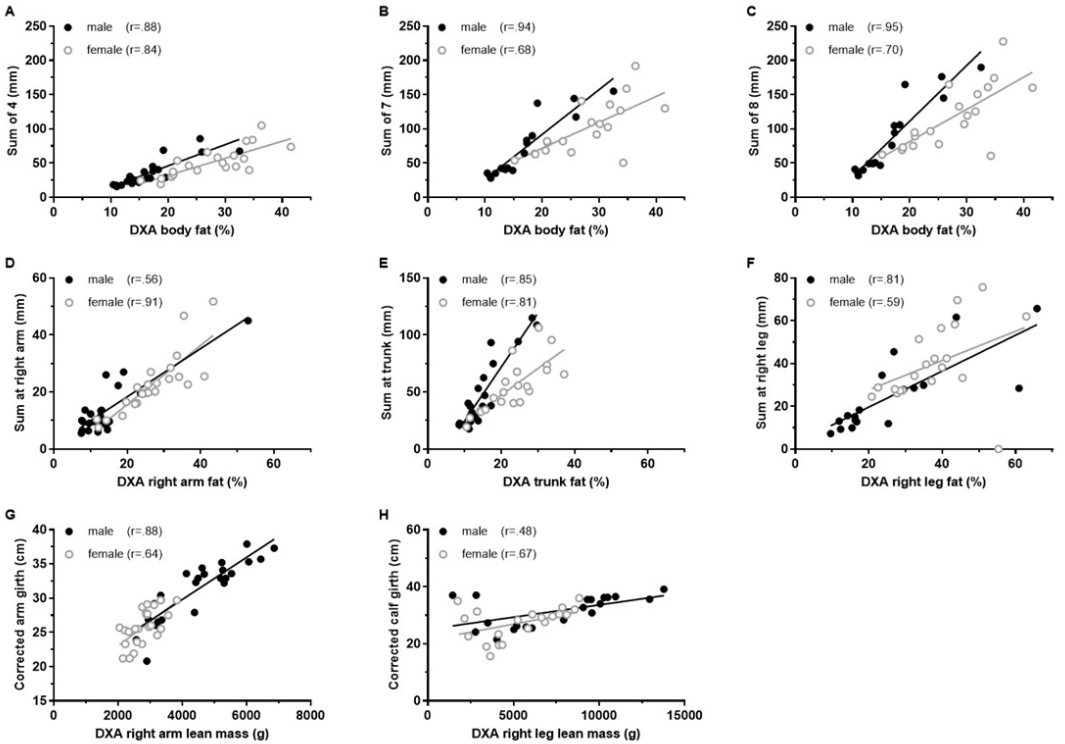

Figure 4.1. Scatter plots showing the correlations between DXA-derived fat percentage and ISAK skinfold thickness in male and female Paralympic athletes. Panel A: Sum of 4 skinfolds vs DXA-derived whole-body fat percentage. Panel B: Sum of 7 skinfolds vs DXA-derived whole-body fat percentage. Panel C: Sum of 8 skinfolds vs DXA-derived whole-body fat percentage. Panel D: Sum of right arm skinfold thickness vs DXA-derived right arm fat percentage. Panel E: Sum of trunk skinfold thickness vs DXA-derived trunk fat percentage. Panel F: Sum of right leg skinfold thickness vs DXA-derived right leg fat percentage. Panel G: Corrected arm girth vs DXA-derived right arm lean mass. Panel H: Corrected calf girth vs DXA-derived right leg lean mass.

weaker for females, particularly for the sum of 7 skinfolds, and the sum of 8 skinfolds. Waist and hip girths correlated strongly with whole-body fat percentage in both males (waist r=.65; P<.001, hip r=.68; P<.05) and females (waist r=.65; P<.001, hip r=.65; P<.05).

When examining site-specific correlations across all participants (Figure 4.1D – F), very strong correlations were found between DXA-derived fat percentage and the sum of skinfolds of the right arm (r=.85; P<.001) and trunk (r=.85; P<.001), while a strong correlation was observed at the right leg (r=.73; P<.001). When addressing the correlation separately for males and females, the correlation between DXA-derived fat percentage and skinfolds of the right arm was moderate in males (r=.56; P=.004) but very strong in females (r=.91; P<.001). At the trunk, both males and females showed very strong correlations between DXA and skinfolds (males: r=.85; P<.001; females: r=.81; P<.001). At the right leg, the correlation between DXA and skinfolds was very strong in males (r=.88; P<.001) but moderate in females (r=.57; P=.009).

Upper arm girths showed very strong correlations with DXA-derived arm lean mass in males (relaxed r=.93, flexed and tensed r=.90; both P<.001), while weaker correlations were observed in females (relaxed r=.19; P=.37, flexed and tensed r=.51; P=.01). Using the (skinfold) corrected arm girth retained a strong correlation in males (r=.88; P<.001), while the correlation became markedly stronger in females (r=.64; P<.001) compared with uncorrected girths. With regard to the legs, uncorrected calf girths showed no significant correlations with right leg lean mass in both males and females, while (skinfold) corrected calf girth was moderately to strongly correlated with leg lean mass (males r=.48, females r=.67; both P<.01)(Figure 4.1G – H).

After converting skinfold thickness to body fat percentage by prediction equations, very strong correlations (range: r=.81 to r=.93) between DXA-derived body fat percentage and skinfold-based prediction equations were seen when assessed over all participants (Figure 4.2). When analysing males and females separately, the correlation coefficients remained strong to very strong for males, but became substantially weaker for females. Only the Wilmore and Behnke and Withers equations showed very strong correlations for both males (r=.94 and r=.92; P<.001) and females (r=.81 and r=.88; P<.001; Table 4.3).

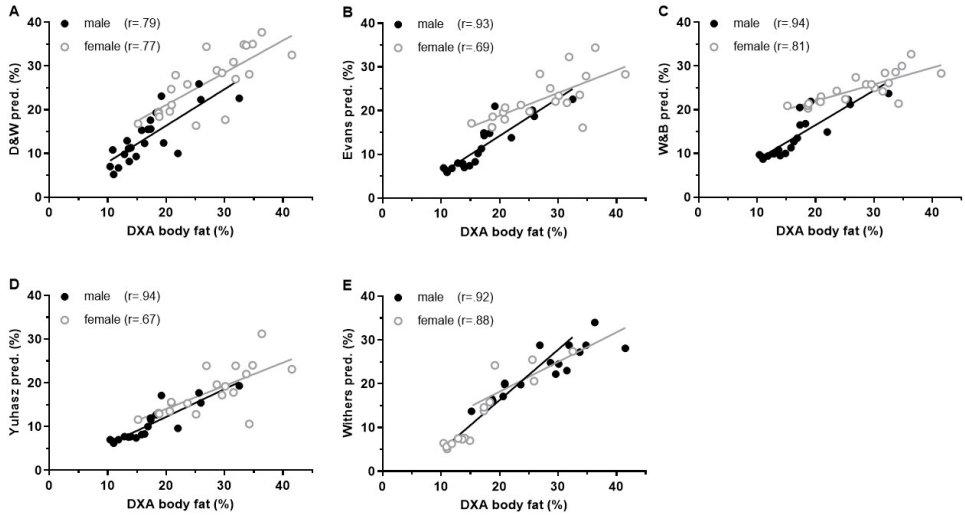

Figure 4.2. Scatter plots showing the correlations between fat percentage derived by DXA and skinfold-based prediction equations. Panel A: Durnin & Womersley (D&W) vs DXA. Panel B: Evans et al. vs DXA. Panel C: Wilmore & Behnke (W&B) vs DXA. Panel D: Yuhasz vs DXA. Panel E: Withers vs DXA.

Table 4.3. Correlations between DXA-derived body fat percentage and ISAK skinfolds and skinfold-based prediction equations for body fat percentage.

	Total (r)	Male (r)	Female (r)
DXA body fat percentage (%)			
Triceps skinfold	.90**	.85**	.89**
Subscapular skinfold	.74**	.80**	.72**
Biceps skinfold	.77**	.67**	.55**
Iliac crest skinfold	.73**	.88**	.74**
Supraspinale skinfold	.72**	.85**	.65**
Abdominal skinfold	.71**	.88**	.68**
Front thigh skinfold	.83**	.87**	.62**
Medial calf skinfold	.84**	.94**	.56*
Σ4 skinfolds (mm)	.85**	.88**	.84**
Σ7 skinfolds (mm)	.83**	.94**	.68**
Σ8 skinfolds (mm)	.83**	.95**	.70**
Durnin & Womersley (%)	.88**	.79**	.77**
Evans (%)	.91**	.93**	.69**
Wilmore & Behnke (%)	.93**	.94**	.81**

Table 4.3. Correlations between DXA-derived body fat percentage and ISAK skinfolds and skinfold-based prediction equations for body fat percentage. (*continued*)

	Total (r)	Male (r)	Female (r)
Yuhasz (%)	.90**	.94**	.67**
Withers (%)	.81**	.92**	.88**

Data are presented as correlation coefficients. *Statistically significant at P<0.05. **Statistically significant at P<0.01.

Agreement between DXA-derived body fat percentage and skinfold-based prediction equations for body fat percentage

The agreement between DXA-derived body fat percentage and the four skinfold-based prediction equations was assessed using Bland-Altman analysis (Figure 4.3). All equations underestimated body fat percentage compared to DXA. The Durnin & Womersley equation showed the lowest mean bias (-2.0%), followed by Wilmore & Behnke (-2.7%), Evans (-4.9%), Withers (-5.3%) and Yuhasz (-7.9%). Limits of agreement were relatively wide for all equations, with Wilmore and Behnke showing the narrowest range (-10.5 to 5.1%), followed by Evans (-12.8 to 3.0%), Yuhasz (-16.5 to 0.7%), Durnin & Womersley (-10.6 to 6.7%), and Withers (-16.5 to 5.7%).

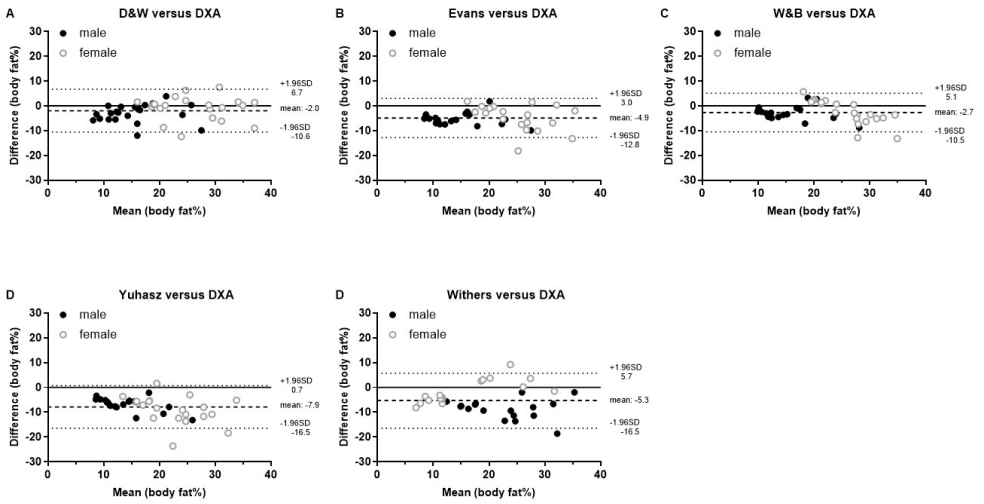

Figure 4.3. Bland-Altman plots showing the agreement between body fat percentage as assessed by DXA and a skinfold-based prediction equation. Panel A: Durnin & Womersley (D&W) prediction equation vs DXA. Panel B: Evans et al. prediction equation vs DXA. Panel C: Wilmore & Behnke (W&B) prediction equation

vs DXA. Panel D: Yuhasz prediction equation vs DXA. Panel E: Withers prediction equation vs DXA. The horizontal dashed line represents the mean difference (bias) between the two methods. The dotted lines represent the 95% limits of agreement (mean difference ± 1.96 SD).

DISCUSSION

This study provides novel insights into Paralympic athletes' body composition assessed using DXA and ISAK skinfold thickness assessment. DXA was successfully conducted in all participants, demonstrating high feasibility. In contrast, completing an ISAK skinfold thickness assessment of 8 skinfolds had a lower success rate due to amputations, deformities, and limb deficiencies. Despite these limitations, strong correlations were observed between DXA-derived body fat percentage and ISAK skinfold thickness assessment. However, when skinfolds were converted to body fat percentages using established equations, the resulting body fat percentages were structurally lower when compared to DXA.

Body composition of Paralympic athletes

Assessing body composition is crucial for evaluating athletes' health and performance [25,26]. Although data on able-bodied athletes are abundant [27], little is known about the body composition and its assessment in Paralympic athletes. In the current study, DXA measurements revealed median body fat percentages of 16.3% in males and 27.8% in females. Besides these obvious sex differences, substantially higher DXA-derived body fat percentages were seen in wheelchair users compared with non-wheelchair users (males: 17.8% vs 13.7%; females: 32.5% vs 25.1%). Notably, these DXA-derived values are generally lower than those reported in previous DXA-based studies of both wheelchair [28–33] and non-wheelchair athletes [28,31,32,34,35]. The lower body fat percentages may reflect the high-performance level of our cohort but could also be related to differences in sport type, underlying disabilities, or the use of different DXA systems across studies. The disparity between wheelchair and non-wheelchair users likely stems from limited mobility and lower-body muscle atrophy associated with impairments such as paraplegia, limb deficiencies, or limb deformities [36,37]. Indeed, further DXA analyses of body fat distribution indicate that wheelchair users had lower lean mass and greater relative fat mass in the legs and trunk, while such differences were absent in the arms. The higher relative fat mass and lower lean mass at the legs were also reflected by the greater leg skinfold thickness in combination with markedly smaller skinfold-corrected calf girths. These findings

align with and confirm the observations by previous smaller studies investigating body fat distribution in wheelchair versus non-wheelchair in athletes with an impairment [28,30,32].

Feasibility and accuracy of ISAK compared with DXA

Several studies assessed skinfold thickness in Paralympic athletes [28,34,38-40]. While most did not report the feasibility of this approach, Goosey-Tolfrey *et al.* [40] demonstrated that an 8-site skinfold assessment could be completed in 27 out of 30 participants (90%). In the current study, DXA was successfully conducted in all participants, while the sum of 4, 7, and 8 skinfolds according to the ISAK protocol was only feasible in 88, 73, and 73% cases, respectively. Among wheelchair users, the success rate of complete 8-site skinfold profile even dropped below 35%. This low success rate was primarily due to specific disabilities such as amputations, deformities, and limb deficiencies, which hindered proper assessment of skinfold thickness according to ISAK standards, especially in the lower extremities. Although modifying the ISAK landmarking procedures could have improved the success rate, such changes would compromise the reproducibility of the skinfold thickness assessment. Therefore, when using skinfold thickness to assess body composition in Paralympic athletes, feasibility must be considered. Given that the sum of 8 skinfolds is generally recommended as the preferred skinfold-based metric for athletes [6], our findings suggest that this approach is not be feasible for a substantial part of Paralympic athletes.

Regardless of feasibility, very strong correlations were observed between the sum of 4, 7, and 8 skinfolds and whole-body fat percentage as assessed by DXA. This indicates that a greater sum of either 4, 7, or 8 skinfolds reflects higher body fat percentages. This finding confirms previous observations in male wheelchair athletes [28,40] and able-bodied athletes [7-10]. Furthermore, our findings demonstrate that DXA-derived regional body fat is closely related to the sum of skinfolds from the corresponding body regions, as indicated by the moderate to very strong correlations. In addition, skinfold-corrected upper arm and calf girths provide insights into regional lean mass and may be useful for tracking changes in lean mass that may occur independently of skinfold thickness. Interestingly, stronger correlations between skinfolds and DXA-derived body fat percentage were generally observed in males compared with females (Fig 1). This disparity can be attributed to the skinfolds of the lower body (medial calf- and thigh skinfold site). For example, the correlation between the sum of the medial calf and thigh skinfold site and DXA-derived leg fat

percentage was much weaker in females (r=.59) compared with males (r=.81). A possible explanation for this finding is sex-specific morphological differences of skin, subcutaneous adipose tissue, and connective tissue architecture [41], which may complicate the accurate execution of ISAK skinfold thickness assessment in females. Indeed, our experience is that at the medial calf and thigh skinfold sites, it is more difficult in females than in males to clearly separate the double layer of skin and subcutaneous fat from deeper tissues with calipers. This likely reduces the accuracy of leg skinfolds as indicators of fat mass. While this challenge also affects non-disabled athletes, disabilities such as leg muscle atrophy can further complicate reliable medial calf and thigh measurements in female Paralympic athletes.

Another key concern in applied settings is the desire to express body fat measurements as a body fat percentage. In the current study, we evaluated four skinfold-based prediction equations for estimating body fat percentage using ISAK skinfold sites applicable in both males and females. The body fat percentages derived from theses equations strongly correlated with DXA-derived body fat percentages (Fig 2). However, skinfold-based prediction equations consistently underestimated DXA-derived body fat percentages. Additionally, the wide limits of agreement indicate substantial individual measurement error. Thus, despite the strong correlations, skinfold-based prediction equations failed to accurately reflect the 'true' body fat percentage on an individual level. For this reason, many researchers have attempted to generate population-specific skinfold-based prediction equations, such as those for subpopulations of Paralympic athletes [34,40]. While these population-specific prediction equations may reduce mean bias relative to a reference method, substantial individual measurement error persists.

Practical implications and considerations

Our results indicate that DXA is the preferred method for assessing body composition in Paralympic athletes. It demonstrates high feasibility in this population and allows for the evaluation of fat mass, fat-free mass, and bone mineral content, including regional analyses of these compartments. When DXA is unavailable or when frequent assessments are needed, skinfold measurements according to ISAK may serve as a practical alternative, provided their limitations are carefully considered. Specifically, skinfold-based prediction equations for estimating body fat percentage should be avoided as they consistently underestimate fat mass and lack accuracy at individual level. Skinfold thickness itself

should be the preferred outcome variable. Although the sum of 8 skinfolds is recommended as the preferred metric in athletes [6], its feasibility is low in Paralympic athletes due to lower-body disabilities. Therefore it seems more appropriate to determine and use a 'sum of feasible skinfold sites' to track body fat at an individual level, rather enforcing a universal skinfold metric across all Paralympic athletes. Furthermore, skinfold-corrected upper arm and calf girths provide additional insights into regional lean mass.

Limitations

In the current study, body fat has been assessed by skinfold thickness measurements and compared to DXA as the criterion method. Although DXA is widely used and accepted as a reference method, the four-compartment model is generally considered the gold standard for body composition assessment. Some studies strongly support the accuracy of DXA when compared to the four-compartment model [42], whereas others have reported somewhat greater individual error [5]. Such individual error may be more pronounced in populations with impairments, such as muscle atrophy, where altered hydration and tissue composition may reduce DXA accuracy [43-45]. Furthermore, this study evaluated skinfold thickness assessment against DXA in a cross-sectional context. As such, the study design does not provide insight into how well ISAK skinfold assessment reflect changes in body fat over time. Future research should therefore examine the accuracy of ISAK skinfold thickness assessment to track longitudinal changes in body composition relative to DXA.

CONCLUSION

This study provides valuable insights into the body composition of Paralympic athletes, highlighting differences between wheelchair and non-wheelchair users. Although DXA was highly feasible, ISAK standardised skinfold assessment was more challenging, as limb deficiencies or deformities often hindered proper landmarking, yielding a relatively low success rate for a full 8-site profile. Nonetheless, skinfold thicknesses remained strongly associated with DXA-derived body fat, supporting their use as a practical field-based alternative. Based on these findings, we recommend measuring all skinfolds that can be obtained according to ISAK standards and interpreting them as a 'sum of feasible skinfold sites', rather enforcing a universal skinfold metric across all Paralympic athletes.

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Chapter 5

Do Paralympic athletes suffer from brittle bones? Prevalence and risk factors of low bone mineral density in Paralympic athletes

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ABSTRACT

Background: Bone health may be a concern in Paralympic athletes, given the presence of multiple risk factors predisposing these athletes to low bone mineral density (BMD). Objective: We aimed to assess the prevalence of low BMD among Paralympic athletes participating in various sport disciplines, and to identify potential risk factors for low BMD. Methods: Seventy Paralympic athletes, of whom 51% were wheelchair-dependent, were included in this cross-sectional study. BMD of the whole-body, lumbar spine, total hip, and femoral neck were assessed by dual-energy x-ray absorptiometry. Comparisons between groups were conducted by one-way ANOVA, and regression analyses were conducted to identify potential risk factors for low BMD. Results: The prevalence of low BMD (Z-score <-1.0) was highest at femoral neck (34%), followed by total hip (31%), whole-body (21%), and lumbar spine (18%). Wheelchair-dependent athletes had significantly lower BMD Z-scores compared to the non-wheelchair-dependent athletes at whole-body level (-0.5±1.4 vs 0.2±1.3; P=0.04), total hip (-1.1±1.2 vs 0.0±1.1; P<0.01), and femoral neck (-1.0±1.3 vs -0.1±1.2; P<0.01). At the lumbar spine, low BMD was completely absent in wheelchair basketball and tennis players. Regression analyses identified body mass, wheelchair dependence, and type of sport, as the main risk factors for low BMD. Conclusions: In this cohort of Paralympic athletes, low BMD is mainly present at the hip, and to a lesser extent at the whole-body and lumbar spine. The most prominent risk factors for low BMD in Paralympic athletes are related to mechanical loading patterns, including wheelchair use, the type of sport, and body mass.

INTRODUCTION

Physical activity generally has a positive impact on bone mineral density (BMD) (1). In particular, high impact sports (e.g. rugby, running, weight lifting) are associated with a high BMD (2). In contrast, athletes of aesthetic or endurance sports are at risk for a low BMD, especially when the sport only involves low impact forces (e.g. cycling, swimming) (3-5). Such a low BMD may predispose athletes to (stress)fractures as well as early osteoporosis (6). Therefore, acquiring a high peak bone mass early in life can prevent health issues both during and after the athletes' career.

While substantial knowledge on BMD is available in non-disabled athletes, such knowledge is currently limited for Paralympic athletes. Two relatively small studies indicated that ~45 to 50% of the Paralympic had low BMD (Z score ≤1) in at least one skeletal site (7, 8), although the prevalence of low BMD seemed substantially lower at individual skeletal sites (8). In non-athletic adults with disabilities, the prevalence of low BMD is high. For example, Smith *et al.* (9) found that more than 50% of this population has low BMD in at least one skeletal site. Possible risk factors for low BMD in this population are a reduced ambulatory status and a longer duration of the disability (9). Indeed, athletes with a spinal cord injury, who are predominantly wheelchair-dependent, had a significantly lower BMD both in the legs and at a whole-body level compared to non-disabled athletes (10). This finding in wheelchair-dependent athletes is likely attributed to the limited mechanical loading of the lower body, resulting in a lack of osteogenic stimulation (11). Aberrant mechanical loading can also be present in athletes with prostheses or abnormal gait patterns (e.g., cerebral paresis athletes), thereby affecting bone remodeling. Besides mechanical loading, insufficient dietary intakes can negatively affect BMD. In particular, low energy availability, which is defined as having insufficient energy to support the normal body functions, because of a mismatch between energy intake and exercise energy expenditure (12), has a negative effect on BMD (13). Based on hormonal markers of low energy availability, like low estradiol, insulin like growth factor 1, or triiodothyronine (T3), Paralympic athletes seem to be at risk for low energy availability (14) and, therefore, low BMD as well (15). Another risk to bone health in Paralympic athletes may be the use of certain medications such as anticonvulsants, corticosteroids, or thyroid hormones to combat the symptoms or comorbidities associated with their disability (16-18). Despite the apparent increased risk for low

BMD in Paralympic athletes, the prevalence and associated risk factors have yet to be established.

Regardless of the causes, it has been speculated that low BMD may predispose Paralympic athletes to traumatic fractures, even after minor falls or collisions (19). This can be attributed to the increased fall risk due to reduced coordination (e.g. cerebral palsy), loss of proprioception (e.g. running on protheses), or unforeseen obstacles (e.g. visual impairment) (19). Athletes with spina bifida or spinal cord injury may lack the sensation of a fracture in the lower body (20), which can lead to a late diagnosis and treatment, thereby impeding the healing process and potentially necessitating surgical intervention and resulting in long-term impairment (21). Furthermore, fractures could hinder effective training and competitive participation, and even compromise athletes' independence due to limitations in performing daily activities (22). Besides traumatic fractures, low BMD may also predispose athletes to stress fractures. For example, among US Paralympic athletes the prevalence of sports related stress fractures, after the onset of disability is 9.2% (23). Before defining effective prevention and treatment strategies to combat low BMD in Paralympic athletes, it remains to be determined which Paralympic athletes are at risk and what risk factors contribute to the development of low BMD in this population.

The current study evaluated BMD at different skeletal sites within a substantial cohort of Paralympic athletes with various disabilities across multiple sports. Additionally, this study investigated potential risk factors associated with low BMD in this population.

METHODS

Study design

In this cross-sectional study, the BMD, body composition, training load, and blood markers of energy availability and bone status were assessed in Paralympic athletes (n =70). This study was part of a larger collaborative study on the nutritional requirements of Paralympic athletes. Data were collected between September 2020 and September 2022 at the (mobile) sport and research center of HAN University of Applied Sciences (Nijmegen, The Netherlands) and at the department of Physical Performance at Norwegian School of Sport Sciences (Oslo, Norway). The study was approved by the Medical Ethical Committee Zuyd (NL72682.096.20)

in the Netherlands and the Regional Committee for Medical and Health Research Ethics (REK 102284) in Norway.

Participants

Paralympic athletes competing in Para cycling (*n*=17), wheelchair tennis (*n*=9), wheelchair basketball (*n*=18), Para alpine skiing (*n*=8), Para Nordic skiing (*n*=7) and other sports (n=11; including Para swimming (*n*=4), wheelchair rugby (*n*=2), Para orienteering (*n*=1), Para badminton (*n*=1), Para rifle shooting (*n*=1), Para snowboarding (*n=1*), and boccia (*n*=1)), were recruited via the national coaches of the Dutch and Norwegian Olympic/Paralympic sport federations. In this exploratory study on the prevalence of low BMD among Paralympic athletes from the Netherlands and Norway, invitations were extended to all respective Paralympic teams. Without conducting a specific sample size calculation, we aimed to include any athlete from these teams willing to participate. Inclusion criteria were elite or talent level Paralympic athletes involved in a national sport program, aged 16 to 50 y. Multiple disabilities were included and categorized as spinal cord disorder, neurological impairment, amputation/dysmelia, visual/hearing impairment, and other disabilities. Participants were classified as 'wheelchair dependent' if more than 50% of their ambulatory activities outside of sports were performed in a wheelchair. Exclusion criteria were the presence of serious injuries that restricted regular training, and pregnancy or lactation. All participants were informed about the nature and potential risks of the study and signed an informed consent according to code of ethics of the Declaration of Helsinki (24).

Study procedures

Participants arrived at our (mobile) laboratories in the morning (between 7:00 and 10:00 h) in an overnight fasted state. Before the dual energy x-ray absorptiometry (DXA) scans, body mass was determined with a digital scale (Seca 770 and Seca 887, Hamburg, Germany, for the Netherlands and Norway respectively) and stature was determined with a mobile stadiometer (Seca 213i and Seca 437, Hamburg, Germany, for the Netherlands and Norway respectively). When the participants were unable to stand up straight, stature was measured from head to heel in supine position. Furthermore, a fasted venous blood sample was drawn, and an interview with specific questions about the sport and disability of the Paralympic athletes was conducted.

Bone mineral density and body composition

Three DXA systems were used, two in the Netherlands (Horizon and Discovery A, Hologic, MA, USA) and one in Norway (Lunar iDXA, GE Healthcare, Madison, USA). Whole-body BMD (g/cm^2), lumbar spine (L1-L4) and left proximal femur (femoral neck and total hip) were determined by DXA procedures as recommended by the National Health and Nutrition Examination Survey (NHANES) (25), using the system's software package (Hologic Horizon: Apex version 5.6.0.5, Hologic Discovery A: Apex version 4.5.3, Lunar iDXA: enCORE version 18). If a major implant was placed in the lumbar spine, the lumbar spine and whole-body scan were excluded. Minor metal implants, for example in the collarbone and wrist area, were omitted with the DXA software and the scans were included in analyses. Furthermore, in case the left hip was disformed because of the disability, hindering proper analysis (e.g., the neck box could not be placed at the femoral neck), the right hip was scanned and analyzed. If the same problem was encountered at the right hip, the hip scan was excluded for the femoral neck, but not for the total hip. Similarly, when the lumbar spine had severe scoliosis where the vertebrae could not be distinguished from each other, the lumbar spine scan was excluded. In addition to absolute BMD values, standardized BMD values were calculated for the lumbar spine, total hip and femoral neck according to the equations by Hui *et al.* (26) (for the lumbar spine) and by Lu *et al.* (27) (for the total hip and femoral neck), to account for potential discrepancies between the different DXA manufacturers. Furthermore, BMD values were standardized to Z-scores using age, ethnicity, and sex normative reference values of the respective DXA systems. The BMD Z-scores were used to assess the prevalence of low BMD (Z-score ≤-1.0) and osteoporosis (Z-score ≤-2.0), based on the ACSM classifications for athletes (28). In addition to BMD, measurements of whole-body and regional body composition were performed, according to recommended standardization procedures (29), using the classic calibration algorithm (without NHANES correction). The DXA systems were calibrated according to manufacturer's instructions, in the morning before measurements took place.

Blood markers

Fasted venous blood samples were taken from the antecubital vein. The blood samples were allowed to clot for ~30 min and centrifuged at 1000g for 15 min. Subsequently, aliquots of serum were stored at −80°C, until further analysis. Serum samples were analyzed by the Central Diagnostic Laboratory at the Maastricht University Medical Centre (The Netherlands) for T3, as marker of energy availability, and vitamin D (25-(OH) D), procollagen 1 intact n-terminal propeptide (P1NP) and C-terminal telopeptide 1 (CTX-I) as markers of bone status. Total T3 was determined with a chemiluminescent immunoassay (Immulite XPi instrument, Siemens Healthcare Diagnostics). Intact P1NP, CTX-I, and 25(OH)D were measured using chemiluminescence immunometric assays on the IDS-iSYS instrument (Immunodiagnostic Systems Holdings, PLC, Tyne and Wear, UK). Reliability (CV) values for between-day measurements were ≤9% (CTX-I), ≤5% (P1NP), ≤10% (T3), and ≤9% (25(OH)D). Low T3 was defined as <0.8 nmol/L and low vitamin D was defined as <50 nmol/L. Low P1NP, or CTX-I were based on reference values according to age and gender (Supplemental Table S5.1).

Exercise training

All participants were asked to keep a training log with information on the timing, type and duration of all training sessions or competitions during a 14-day period. Some participants already tracked such data in a digital app, while the other participants were provided a written training log to record training data. Exercise duration was extracted from all exercise training logs and mean daily exercise duration served as a universal exercise training metric across sports.

Table 5.1. Participants' characteristics.

Sport	Total (n=70)	Para cycling (n=17)	Wheelchair tennis (n=9)	Wheelchair basketball (n=18)	Para alpine skiing (n=8)	Para Nordic skiing (n=7)	Other (n=11)
Disabilities (*n*)							
Spinal cord injury	21	2	3	9	3	2	2
Neurological disorder	10	5	0	0	0	2	3
Dysmelic/amputation	18	5	5	3	3	1	1
Visual/hearing impaired	7	2	0	0	2	1	2
Other	14	3	1	6	0	1	3
Wheelchair dependent (no/yes)	34/36	12/5	2/7	7/11	3/5	4/3	6/5
Acquired at birth (no/yes)	34/36	8/9	3/6	14/4	4/4	3/4	2/9
Time since disability (years)	21±11	22±13	26±9	17±8	20±7	21±12	23±11
Sex, male/female (*n*)	34/36	9/8	5/4	5/13	4/4	4/3	7/4
Age (years)*	25 (21-33)	26 (23-32)	27 (22-33)	26 (21-30)	28 (22-41)	23 (19-34)	21 (18-40)
Body height (cm)*	169 (160.4-180.0)	169.7 (164.0-185.8)	168.0 (140.9-176.5)	170.0 (153.1-179.3)	168.7 (129.1-174.8)	165.0 (151.1-180.0)	169.9 (160.0-180.0)
Body mass (kg)*	64.7 (55.5-72.5)	70.6 (55.7-73.7)	63.1 (53.4-68.2)	61.9 (56.6-78.6)	64.6 (61.4-71.9)	59.2 (51.0-72.5)	65.4 (55.3-69.5)
Lean body mass (kg)	47.4±10.7	50.2±12.0	46.5±8.0	46.3±11.2	46.6±6.3	44.8±10.4	47.9±13.7

Table 5.1. Participants' characteristics. (*continued*)

Sport	Total (n=70)	Para cycling (n=17)	Wheelchair tennis (n=9)	Wheelchair basketball (n=18)	Para alpine skiing (n=8)	Para Nordic skiing (n=7)	Other (n=11)
Training duration (h/ week)	11.5±4.8	12.4±4.1	15.2±5.6	8.5±1.3[a]	7.7±1.1[a]	13.8±3.3	9.3±5.9
T3 (nmol/L)*	1.39 (1.28-1.66)	1.27 (1.12-1.53)	1.42 (1.30-1.53)	1.36 (1.22-1.63)	1.53 (1.17-1.73)	1.37 (1.31-1.39)	1.67 (1.35-1.89)
Vitamin D25 (nmol/L)	67.2±19.5	78.8±20.2	62.4±12.8	63.4±16.6	73.1±20.8	62.9±17.0	58.4±23.0
P1NP (ng/mL)	82.2±35.3	84.9±27.6	71.0±33.8	70.8±37.4	90.7±34.4	74.0±21.8	105.4±43.8
CTX (ng/mL)	0.47±0.31	0.56±0.38	0.43±0.25	0.35±0.24	0.47±0.33	N.A.	0.72±0.31

Frequencies are presented as number of cases (*n*). Normally distributed data are presented as mean±SD, while non-normally distributed data (*) are presented as median (Q1-Q3). No values for CTX for the Norwegian athletes were reported due to a technical error. The sports included in other sports: para swimming (*n*=4), wheelchair rugby (*n*=2), para orienteering (*n*=1), para badminton (*n*=1), para rifle shooting (*n*=1), para snowboarding (*n*=1), boccia (*n*=1) and wheelchair racing (*n*=1). T3 = tri-iodothyronine; P1NP = procollagen 1 intact n-terminal propeptide; CTX = C-terminal telopeptide 1; N.A. = not applicable. [a] = significantly different from wheelchair tennis $P<0.05$.

Data-analysis

All data were checked for normality with the Kolmogorov-Smirnov test. Normally distributed data are presented as means±SD, while non-normally distributed data are presented as median (Q1-Q3). Differences between wheelchair-dependent and independent athletes were analyzed with an unpaired t-test for normally distributed data or a Mann-Whitney U-test when the data was non-normally distributed. Differences between sports were analyzed with a one-way ANOVA with Bonferroni correction for normally distributed data or a Kruskal-Wallis test when the data was non-normally distributed. Correlations were analyzed with either Pearson's correlation coefficient (normally distributed data) or Spearman's correlation coefficient (non-normally distributed data). Furthermore, multiple regression analyses with backward selection were conducted, with BMD Z-scores at different measurement sites (whole-body, lumbar spine, total hip, and femoral neck) as dependent variables. Potential risk factors for low BMD in Paralympic athletes were used as independent variables, including, body mass, years since disability onset, wheelchair dependence, vitamin D status, T3 (as a marker of energy availability), and type of sport (with the 'other sports' category being used as reference category). All statistical analyses were conducted with SPSS 27.0 (IBM Corp., Armonk, NY), with statistical significance set at $P< 0.05$.

RESULTS

Participants

A total of 70 male (n=34) and female (n=36) Paralympic athletes were included (Table 5.1). Together, these athletes won a total of 11 gold, 6 silver, and 8 bronze medals during the last two Paralympic games (Tokyo 2020 and Beijng 2022, respectively). Athletes were classified as either having a spinal cord disorder (including spina bifida, traumatic and non-traumatic spinal cord injury; n=21), neurological disorder (including cerebral palsy and other neurological disorders; n=10), dysmelic or amputation (n=18), a visual or hearing impairment (n=7) or 'other disabilities' (n=14). Other disabilities included nerve damage in the lower extremities, complex regional pain syndrome, intellectual impairments, spondylitis, connective tissue disease, muscular dystrophy, hip dysplasia, Perthes disease and arthrogryposis. Of all athletes 51% were classified as wheelchair-dependent. Some athletes used medication that may interfere with bone metabolism, i.e., corticosteroids (n=2), anticonvulsant (n=1), and thyroid hormone (n=1) during the study period, and a cortico-

steroid injection in the last six months before the study (n=1). As shown in Table 5.1, no statistical differences were found between sports for any of the participant characteristics, except for training duration. None of the athletes exhibited a T3 concentration outside of the reference range (0.8 to 2.6 nmol/L). Eleven participants (17%) had suboptimal levels of vitamin D (<50nmol/L), with one participant having a severe vitamin D deficiency (<30 nmol/L). As shown in Table 5.2, wheelchair-dependent athletes had lower body height, body mass, lean body mass and serum P1NP concentrations, and higher age compared with non-wheelchair-dependent athletes.

Bone mineral density

A total of 8, 10, 3 and 11 scans of the whole-body, lumbar spine, total hip, and femoral neck, respectively, had to be excluded due to the presence of metal implants or deformations of the spine or hip. Additionally, the right instead of the left hip was analyzed for 6 participants because of deformations or metal in the left hip.

Across all participants, the mean BMD Z-scores were -0.1±1.4, 0.0±1.3, -0.5±1.3 and -0.5±1.3 at the whole-body, lumbar spine, total hip, and femoral neck respectively (Figure 5.1 and Table 5.2). The prevalence of low BMD (Z-score <-1.0) was highest at the femoral neck (34%), followed by the total hip (31%), whole-body (21%) and lumbar spine (18%). The prevalence of osteoporosis (Z-score <-2.0) was highest at the total hip (15%), followed by the femoral neck (12%), lumbar spine (8%), and whole-body (8%).

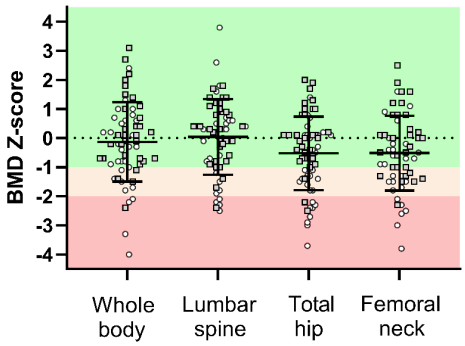

Figure 5.1. Bone mineral density Z-scores in all Paralympic athletes at different measurement sites. Data are presented as individual scores, while the horizontal bars with error bars represent means±SD. Gray squares = Non-wheelchair-dependent athlete; white circles = wheelchair-dependent athlete; BMD = bone mineral density.

When examining the sports categories separately (Table 5.3), the prevalence of low BMD at the whole-body level (Figure 5.2A) was absent for the Para alpine skiers and Para Nordic skiers, with mean BMD Z-scores well above zero (0.3±1.4 and 1.1±0.8, respectively). The mean whole-body BMD Z-scores for Para cycling, wheelchair tennis, wheelchair basketball and 'other sports' were -0.3±1.0, -0.5±1.0, -0.6±1.3 and -0.1±2.0, respectively. No significant differences between the BMD Z-scores of the whole-body were found between sports.

At the lumbar spine (Figure 5.2B), low BMD was absent in wheelchair tennis and wheelchair basketball athletes. Mean BMD Z-scores were significantly higher in wheelchair basketball players (1.2±1.0) compared with Para cycling (-0.6±1.0), Para alpine skiing (-0.6±0.8), Para Nordic skiing (-0.5±1.1), and 'other sports' (-0.4±1.4; $P<0.05$ for all comparisons). Wheelchair tennis players also had a significantly higher BMD Z-scores at the lumbar spine (0.9±0.9) compared with the Para cyclists ($P=0.04$).

At the total hip (Figure 5.2C), the mean BMD Z-scores were -1.0±1.4, -0.3±1.2, -0.4±1.0, -0.5±1.1, -0.4±0.9 and -0.3±1.7 for the para-cyclists, wheelchair tennis, wheelchair basketball, alpine skiers, Nordic skiers, and 'other sports' athletes respectively. No significant differences in mean BMD Z-scores were observed between sports.

At the femoral neck (Figure 5.2D), the mean BMD Z-scores were -0.8±1.4, -0.5±1.5, -0.7±0.9, -0.2±1.0, -0.3±0.9 and -0.1±1.7 for the para-cyclists, wheelchair tennis, wheelchair basketball, alpine skiers, Nordic skiers, and 'other sports' athletes respectively. For this skeletal site, also no significant differences in mean BMD Z-scores were observed between sports.

When comparing BMD Z-scores between wheelchair-dependent and non-wheelchair-dependent athletes, wheelchair-dependent athletes appeared to have significantly lower BMD Z-scores at the whole-body (-0.5±1.4 vs 0.2±1.3; P=0.04), total hip (-1.1±1.2 vs 0.0±1.1; P<0.01) and femoral neck (-1.0±1.3 vs -0.1±1.2; P<0.01), but not at the lumbar spine (-0.1±1.6 vs 0.2±1.0; P=0.20) compared to the non-wheelchair-dependent athletes (Table 5.2).

Regression analyses

As shown in Table 5.4, the final regression model did not reach statistical significance for whole-body BMD Z-score, $F(1,55)=4.009$, P=0.05, adjusted R^2=0.05.

For the lumbar spine BMD Z-score, the final regression model (Table 5.4) contained body mass, wheelchair tennis and wheelchair basketball as factors positively associated with BMD, $F(3, 50)=14.372$, P<0.001, adjusted R^2=0.43.

For the total hip BMD Z-score, the final regression model (Table 5.4) contained body mass as factor positively associated with BMD, while wheelchair dependence and Para cycling were negatively associated with BMD, $F(3, 57)=11.165$, P<0.001, adjusted R^2=0.34.

For the femoral neck BMD Z-score, the final regression model (Table 5.4) contained body mass as factor positively associated with BMD, while wheelchair dependence was negatively associated with BMD, $F(2, 52)=7.741$, P=0.001, adjusted R^2=0.20.

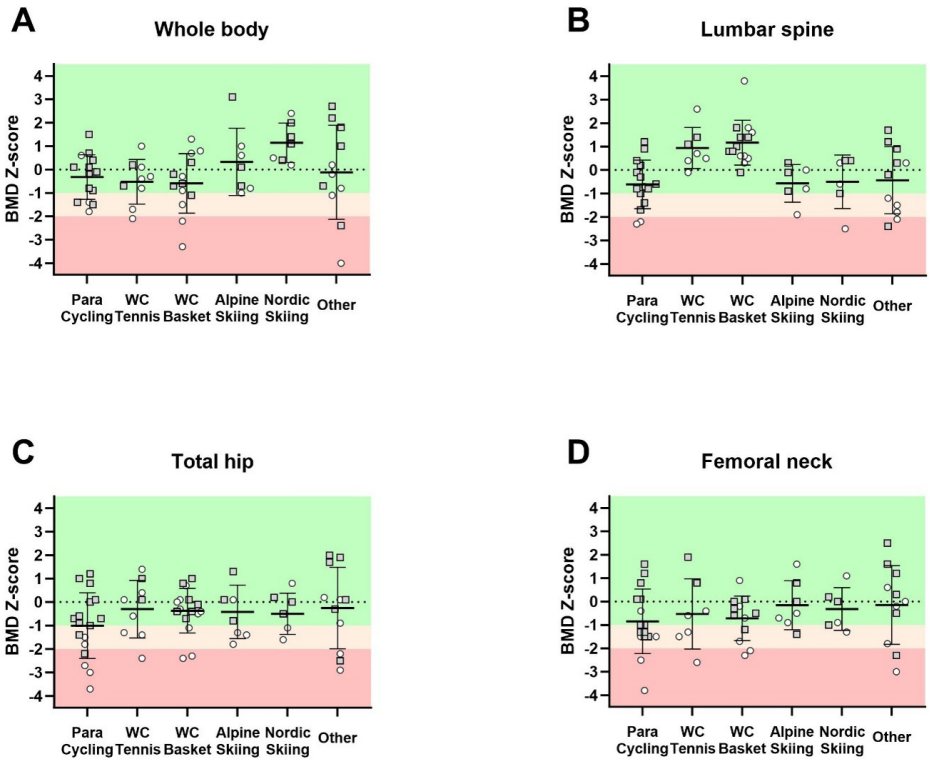

Figure 5.2. The bone mineral density Z-scores at whole-body level (A), lumbar spine (B), total hip (C) and femoral neck (D) for the various sports. At the lumbar spine (B) there is a significant difference in BMD Z-scores between wheelchair tennis players and Para cyclists and between wheelchair basketball players and Para cyclists, alpine skiers, Nordic skiers, and 'other' athletes; $P<0.05$ for all comparisons. Gray squares = Non-wheelchair-dependent athlete; white circles = wheelchair-dependent athlete; BMD = bone mineral density. WC= wheelchair; Basket= basketball.

Table 5.2. Characteristics and bone mineral density of non-wheelchair-dependent and wheelchair-dependent Paralympic athletes.

	Total	Non-wheelchair-dependent	Wheelchair-dependent	P-value
Characteristics				
Age (years)*	25 (21-33)	23 (20-28)	30 (23-40)	**<0.01**
Body height (cm)*	169.0 (160.4-180.0)	175.0 (168.1-180.9)	164.0 (138.0-170.0)	**<0.01**
Body mass (kg)*	64.7 (55.5-72.5)	70.9 (61.3-77.7)	61.4 (52.8-67.3)	**<0.01**
Lean body mass (kg)	47.4±10.7	52.9±11.1	42.3±7.4	**<0.01**

Table 5.2. Characteristics and bone mineral density of non-wheelchair-dependent and wheelchair-dependent Paralympic athletes. (*continued*)

	Total	Non-wheelchair-dependent	Wheelchair-dependent	P-value
T3 (nmol/L)*	1.39 (1.28-1.66)	1.37 (1.27-1.63)	1.40 (1.30-1.68)	0.73
Vitamin D25 (nmol/L)	67.2±19.5	66.8±20.2	67.6±19.2	0.87
P1NP (ng/mL)	82.2±35.3	91.7±34.9	73.7±33.9	**0.04**
CTX (ng/mL)	0.47±0.31	0.55±0.31	0.41±0.30	0.12
Bone mineral density (g/cm2)				
Whole-body	1.134±0.122	1.168±0.122	1.097±0.113	0.02
Lumbar spine	1.083±0.158	1.106±0.142	1.053±0.174	0.20
Total hip	0.916±0.187	0.997±0.164	0.835±0.175	**<0.01**
Femoral neck	0.845±0.199	0.913±0.199	0.770±0.174	**<0.01**
Bone mineral density Z-score				
Whole-body	-0.1±1.4	0.2±1.3	-0.5±1.4	0.04
Lumbar spine	0.0±1.3	0.2±1.0	-0.1±1.6	0.34
Total hip	-0.5±1.3	0.0±1.1	-1.1±1.2	**<0.01**
Femoral neck	-0.5±1.3	-0.1±1.2	-1.0±1.3	**<0.01**
Prevalence of low bone mineral density (n_c/n_t (%))				
Whole-body	13/62 (21)	4/32 (13)	9/30 (30)	0.09
Lumbar spine	11/60 (18)	3/33 (9)	8/27 (30)	0.04
Total hip	21/67 (31)	3/34 (9)	18/33 (55)	<0.01
Femoral neck	20/59 (34)	7/31 (23)	13/28 (46)	0.05
Prevalence of Osteoporosis (n_c/n_t (%))				
Whole-body	5/62 (8)	1/32 (3)	4/30 (13)	0.14
Lumbar spine	5/60 (8)	1/33 (3)	4/27 (15)	0.10
Total hip	10/67 (15)	2/34 (6)	8/33 (24)	**0.04**
Femoral neck	7/59 (12)	1/31 (3)	6/28 (21)	**0.03**

Normally distributed data are presented as mean±SD, while non-normally distributed data (*) are presented as median (Q1-Q3). Low bone mineral density is defined as bone mineral density Z score <-1.0; Osteoporosis is defined as bone mineral density Z-score <-2.0. n_c = number of athletes with low bone mineral density or osteoporosis. n_t = total number of analyzed scans. Statistical differences between wheelchair-dependent and non-wheelchair-dependent athletes in absolute bone mineral density and bone mineral density Z-scores are analyzed with a student t-test. Statistical differences in prevalence of low bone mineral density and osteoporosis are analyzed with a χ^2-test.

Table 5.3. Bone mineral density of the Paralympic athletes from various sports at different skeletal sites.

	Total	Para cycling	Wheelchair tennis	Wheelchair Basketball	Para alpine skiing	Para Nordic skiing	Other
Whole-body (n)	62	15	9	13	7	7	11
BMD (g/cm2)	1.134±0.122	1.118±0.127	1.126±0.070	1.077±0.105	1.187±0.132	1.204±0.076	1.149±0.165
BMD Z-score	−0.1±1.4	−0.3±1.0	−0.5±1.0	−0.6±1.3	0.3±1.4	1.1±0.8	−0.1±2.0
Low BMD (%)	21	27	22	31	0	0	27
Osteoporosis (%)	8	0	11	15	0	0	18
Lumbar spine (n)	59	15	7	14	6	6	11
BMD (g/cm2)	1.083±0.158	0.989±0.128	1.163±0.113	1.168±0.099[a]	1.021±0.146	1.127±0.169	1.080±0.206
sBMD (g/cm2)	1.130±0.162	1.055±0.148	1.245±0.120	1.252±0.102[a]	1.070±0.106	1.070±0.163	1.068±0.180[b]
BMD Z-score	0.0±1.3	−0.6±1.0	0.9±0.9[a]	1.2±1.0[a]	−0.6±0.8[b]	−0.5±1.1[b]	−0.4±1.4[b]
Low BMD (%)	18	27	0	0	17	17	46
Osteoporosis (%)	8	13	0	0	0	17	18
Total hip (n)	66	17	9	16	7	6	11
BMD (g/cm2)	0.916±0.187	0.844±0.212	0.942±0.171	0.913±0.138	0.894±0.139	0.980±0.134	0.989±0.255
sBMD (g/cm2)	0.909±0.183	0.843±0.220	0.956±0.172	0.921±0.134	0.897±0.116	0.921±0.147	0.959±0.239
BMD Z-score	−0.5±1.3	−1.0±1.4	−0.3±1.2	−0.4±1.0	−0.5±1.1	−0.4±0.9	−0.3±1.7
Low BMD (%)	31	41	33	19	43	29	27
Osteoporosis (%)	15	24	11	13	0	0	27
Femoral neck (n)	59	16	7	12	7	6	11
BMD (g/cm2)	0.845±0.199	0.772±0.189	0.813±0.198	0.769±0.105	0.870±0.151	0.984±0.138	0.964±0.274
sBMD (g/cm2)	0.882±0.186	0.832±0.226	0.903±0.215	0.855±0.114	0.935±0.109	0.886±0.158	0.937±0.226
BMD Z-score	−0.5±1.3	−0.8±1.4	−0.5±1.5	−0.7±0.9	−0.2±1.0	−0.3±0.9	−0.1±1.7
Low BMD (%)	34	50	43	33	14	17	27
Osteoporosis (%)	12	13	14	17	0	0	18

Bone mineral density Z-scores are presented as mean±SD. BMD = bone mineral density; sBMD = standardized bone mineral density; low BMD is defined as a Z-score <−1; osteoporosis is defined as Z-score <−2. [a] significantly different from Para cycling $P<0.05$. [b] significantly different from wheelchair basketball $P<0.05$. sBMD is calculated based on the equations by Hui *et al.* (26) (for the lumbar spine) and by Lu *et al.* (27) (for the total hip and femoral neck).

DISCUSSION

The current study revealed that low BMD in Paralympic athletes is mainly prevalent in the hip region. More specifically, BMD of the hip region seemed to be particularly affected in wheelchair-dependent athletes. In contrast, the overall prevalence of low BMD at both the lumbar spine and whole-body level was not notably high. Wheelchair basketball and tennis players even seemed to be fully protected against low BMD of the lumbar spine. Regression analyses identified the type of sport, wheelchair dependence, and body mass as the main predictors of BMD in Paralympic athletes.

Prevalence of low bone mineral density

When considering Z-scores of a normal distribution curve, approximately 16% of the investigated population can be expected to have a low BMD (Z-score <-1). In this regard, the prevalence of low BMD in Paralympic athletes was quite substantial at the total hip (31%) and femoral neck (34%), while the prevalence of low BMD was not notably high at the whole-body level (21%) and lumbar spine (18%). In contrast to our cohort of Paralympic athletes, it has previously been shown that non-athlete individuals with a disability have a considerably higher prevalence of low BMD at the lumbar spine (31%) and at the hip (42%) (9). This supports the notion that sport participation generally exerts a positive effect on BMD in people with a disability (30). Moreover, previous studies have shown that wheelchair-dependent athletes had a slightly, but sometimes significantly, higher BMD at the spine compared to a non-athlete reference population (31, 32). Nevertheless, the Paralympic athletes in our study generally seem to display lower mean BMD Z-scores (33) and a higher prevalence of low BMD Z-scores (34) compared with non-disabled athletes.

The importance of mechanical loading

The high prevalence of low BMD in the hip region can be mainly attributed to the wheelchair-dependent athletes. Indeed, the wheelchair-dependent athletes had a significantly lower BMD at the total hip and femoral neck compared to the non-wheelchair-dependent athletes. This finding was confirmed by the regression analyses, and is consistent with previous research showing that wheelchair athletes have a lower BMD in the legs compared to athletes (10) and non-athletes (32) without a disability. The high prevalence of low BMD among wheelchair-dependent athletes can probably be explained by the low mechanical loading on the

lower body. In this regard, the lack of local mechanical loading prevents proper bone stress and subsequent bone remodeling at specific skeletal sites (11). Mechanical loading is not only affected by wheelchair use, but also by body mass. A higher body mass leads to more mechanical stress on the bones, due to higher gravitational forces, which leads to a higher BMD (35). The relationship between body mass or body mass index and BMD has been well established in the elderly population (35, 36). This positive relationship is also confirmed by the regression analyses in the current study, which identified body mass as a predictor of BMD at the lumbar spine, total hip, and femoral neck, independent of wheelchair dependence.

Differences in bone mineral density between sports

Importantly, the differences in loading patterns between sports, seem to explain a large part of the differences in BMD between sports. Para cycling was identified as an independent risk factor for low BMD at the total hip and femoral neck. Such a low BMD of the hip and femoral neck is also seen in elite road-race cyclists without a disability (5), although in that population low BMD was even more pronounced at the lumbar spine. Consequently, Para cyclists and wheelchair-dependent athletes should be aware of their increased risk of low BMD of the hip region. Therefore, preventive and treatment strategies for bone health should also target the hip region, acknowledging that this might be challenging in wheelchair-dependent individuals. Wheelchair tennis and basketball players exhibited relatively high BMD Z-scores at the lumbar spine, and none of these athletes had a BMD Z-score <-1. These findings suggest that, despite the majority of wheelchair tennis and basketball athletes being wheelchair-dependent (78% and 61%, respectively), the lumbar spine remains protected against low BMD. Apparently, athletes in these particular sports receive highly effective osteogenic stimuli for the lumbar spine. When examining the biomechanics of wheelchair tennis and basketball, it is obvious that these sports involve a significant number of rotational movements that could affect the BMD by generating torsional loading. Previous research has indicated that torsional loading creates the greatest strain upon bone compared with other loading directions (37). Additionally, studies on non-disabled tennis and baseball players have demonstrated that torsional loading on the racket and throwing arm, respectively, account for the biggest changes in BMD (38, 39). As a result, the high levels of torsional loading on the lumbar spine in wheelchair basketball and tennis may explain the differences in BMD Z-scores and the low prevalence of low BMD of the lumbar spine compared with

the other Paralympic sports. These results also illustrate the principle of site-specific loading, since the relatively high BMD of the lumbar spine in these particular sports was not seen at the whole-body level or hip region. It could be suggested that torsional loading should be incorporated within the training programs of Paralympic athletes as a potential protective measure against low BMD of the lumbar spine. Furthermore, to decrease fracture rates it would be interesting to use torsional loading on other skeletal sites with low BMD, where possible.

Other potential risk factors for low bone mineral density

A known risk factor for low BMD is a low energy availability (13). Indeed, we have previously identified serum T3, a marker of low energy availability (28, 40), as predictor of low BMD in elite cyclists (5). In the current study, however, serum T3 concentrations were not associated with BMD. It can be speculated that the heterogenous loading patterns and low mechanical loading due to wheelchair usage and the various sports, may have masked the impact of energy availability on BMD in this population. This argument may also explain why serum vitamin D was not associated with BMD. Moreover, it should be noted that most athletes in our study used vitamin D or multivitamin supplements, and 83% of the athletes had a vitamin D level exceeding 50 nmol/L. Such vitamin D levels may be adequate to support optimal bone health (41). Besides low energy availability and vitamin D status, also the duration of disability has previously been linked to bone health (42). However, we found no association between the duration of disability and BMD. This could be due to the relatively long time since disability onset, averaging 21 years. For example, demineralization of the proximal femur starts within the first 6 months after spinal cord injury, stabilizing at 60-70% of normal values after 12 to 24 months (43, 44). Therefore, it seems likely that the loss of BMD following disability onset has stabilized for most athletes in our study, making it a non-discriminatory risk factor in this cohort. It is also worth noting that 51% of the athletes were congenitally disabled, which could have influenced the potential relationship between time since disability and the BMD.

Strengths and limitations

The strength of the current study is the comprehensive assessment of BMD and associated risk factors in a representative population of Paralympic athletes, covering a large variety of Paralympic sport disciplines and disabilities. Nevertheless, we should also acknowledge some limitations. Inherent to the Paralympic population and variety of sport

disciplines, the current cohort was highly heterogeneous in terms of disabilities and loading patterns. This heterogeneity in loading patterns may have limited the statistical power to identify risk factors for low BMD other than loading-related factors. Secondly, due to the international nature of the study, BMD was assessed at two different research sites using three different DXA systems from two manufacturers. Although this might increase variability in DXA outcomes, operating procedures were standardized across research sites, thereby minimizing potential measurement errors. While absolute BMD values may slightly vary between DXA systems from different manufacturers (26, 27, 45) each manufacturer employs its own reference database, making differences in Z-scores between systems likely negligible. Moreover, to account for potential discrepancies in absolute BMD values across different DXA systems, we have also reported standardized BMD values. A third limitation is that it remains to be established whether low BMD Z-scores in Paralympic athletes are also related to increased risk for traumatic fractures or bone stress injuries. Finally, 34 individual scans had to be excluded from the analysis due to deformities or metal implants. It can be argued that athletes with a deformed hip or lumbar spine receive less mechanical loading at these sites, potentially leading to lower BMD. Consequently, the results reported in this study may underestimate the true prevalence of low BMD in Paralympic athletes.

Conclusions

In this cohort of Paralympic athletes, low BMD is highly prevalent in the hip region, but not necessarily at the lumbar spine. Wheelchair dependence, body mass, and type of sport are the main factors associated with BMD in this population. The relatively high BMD of the lumbar spine in wheelchair tennis and basketball suggests that the typical torsional loadings patterns in these sports may be protective against low BMD of the lumbar spine. The implementation of such torsional loading patterns may warrant consideration in other Paralympic disciplines, as well as in skeletal sites that are susceptible to bone stress injuries or traumatic fractures.

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Conflict of interest

No conflicts of interest, financial or otherwise, are declared by the authors. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. Results of this study were previously presented in poster format at ISENC (international sport and exercise nutrition conference) and additionally an abstract was published in IJSNEM (International Journal of Sport Nutrition and Exercise Metabolism).

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SUPPLEMENTAL

Table S5.1. Reference values for P1NP and CTX according to age and sex.

Sex	Age (years)	P1NP (ng/mL)		Age (years)	CTX (ng/mL)	
		Lower limit	Upper limit		Lower limit	Upper limit
Women	17-20	25.2	160	14-18	0.32	2.62
	21-35	14.7	74.6	>18 & premenopausal	0.05	0.67
	35-50	12.9	66.8			
Men	17-20	28.1	369	14-18	1.02	4.47
	21-45	19.4	95.4	25-29	0.12	0.83
	>45	12.8	71.9	30-34	0.11	0.81
				35-39	0.11	0.78
				40-44	0.10	0.76
				45-49	0.09	0.73

P1NP reference values are based on the study of Morovat *et al.* (1). CTX reference values are based on the study of Michelsen *et al* (2) and Diemar *et al.* (3).

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Chapter 6

Continuous glucose monitoring in para cyclists: An observational study

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ABSTRACT

Continuous glucose monitoring (CGM) is an emerging tool for dietary counseling in athletes. This study aimed to explore blood glucose profiles in Para cyclists and evaluate CGM accuracy at rest and during exercise.

Thirteen Para cyclists, comprising eight hand bikers and five cyclists, wore a CGM sensor (Abbott) for two weeks. Participants recorded the timing of meals and regular training sessions, and executed one standardized training session. Fifteen capillary blood glucose reference values (seven at rest and eight during the standardized training), were obtained by finger pricks. Mean glucose concentrations and time spent in hypoglycemia (<3.9 mmol/L), euglycemia (3.9-7.8 mmol/L) and hyperglycemia (>7.8 mmol/L) were calculated over 24h, and during daytime, nighttime, exercise, and 2h postprandial periods. Mean absolute relative differences (MARD) were calculated between the CGM and capillary blood glucose.

The mean glucose concentration over the 24h period was 5.7 (5.6-5.8) mmol/L. Athletes were in euglycemia 91% of the time. Hyperglycemia was almost exclusively observed postprandially and during exercise. Hypoglycemia was restricted to the night and was particularly observed in athletes with a spinal cord injury. CGM accuracy was acceptable at rest (MARD: 12%), but markedly lower during exercise (MARD: 34%; P=0.01), especially for hand bikers (MARD: 41%) compared with cyclists (MARD: 24%; P=0.01).

Para cyclists generally do not display signs of disturbed glucose regulation. However, the increased risk for nocturnal hypoglycemia in athletes with a spinal cord injury warrants attention. Furthermore, CGM accuracy is compromised during exercise, especially if the sensor is in proximity to highly active muscles.

INTRODUCTION

A continuous glucose monitor (CGM) is a wearable device that automatically monitors blood glucose concentrations over 24h at intervals ranging from 1 to 15 min, depending on the device. CGM devices were originally developed to assist in the blood glucose control in patients with diabetes, and their application has been well studied in this population (1). Over the past decade, CGM devices have been improved in accuracy, longevity, and comfort. Consequently, these devices have garnered interest in the sports community. It is generally believed that monitoring blood glucose concentrations in real-time, can potentially benefit athletes, coaches, and sport nutritionists in optimizing nutritional strategies (2, 3).

It has long been established that hypoglycemia has a negative effect on exercise performance. In this regard, the development of fatigue during prolonged exercise has been linked to hypoglycemia (4), emphasizing the importance of preventing hypoglycemia during exercise. Besides hypoglycemia, hyperglycemia is also believed to detrimentally affect performance, potentially by impairing decision-making, as observed in a case study of an IndyCar driver with type 1 diabetes (5). Chronic hyperglycemia has also been suggested to be a negative regulator of aerobic adaptations to exercise (6). Additionally, hyperglycemia may influence substrate selection during exercise (7), potentially augmenting carbohydrate oxidation and, as such, accelerating muscle and liver glycogen depletion.

Limited evidence suggests that elite athletes spend more time in both hypo- and hyperglycemia compared to healthy controls (8). In this context, hyperglycemia seems to occur mainly in the early afternoon, while hypoglycemia occurs mainly during the night. Nocturnal hypoglycemia can potentially disrupt sleep by triggering an awakening response (9), which decreases sleep efficiency and increases wakefulness (10), thereby potentially impacting physical and mental performance, increasing injury risk and impeding recovery (11, 12). Despite the potential impact of hypo- and hyperglycemia on performance and recovery, information on the prevalence of hypo- and hyperglycemia in athletes without diabetes is quite scarce (8, 13, 14), and fully absent in Paralympic athletes. Such information could be of particular interest for Paralympic athletes, especially those with spinal cord injuries (SCI), who might have impaired counter-regulation to hypoglycemia due to autonomic dysfunction (15).

While the current generation CGM devices is generally accurate and reliable for assessing blood glucose concentrations in non-diabetic individuals (16), their performance during exercise could be an issue of concern. Multiple studies have reported a reduced accuracy during exercise (13, 17-19), with some studies noting an absolute decrease in accuracy (18) or a delay (13, 19) in CGM-derived glucose concentrations when compared to blood glucose concentrations from blood samples collected, while others reported satisfactory accuracy of CGM devices during high-intensity intermittent exercise in people with type 1 diabetes (20).

This study evaluates the blood glucose profiles of Para cyclists by examining the prevalence of hyper- and hypoglycemia, throughout the day and night, during exercise, and following meals. Furthermore, we evaluated the agreement in blood glucose concentrations obtained by the CGM and those obtained via capillary blood glucose sampling, both at rest and during exercise.

METHODS

Study design

In this cross-sectional study, blood glucose concentrations of Para cyclists were monitored for up to fourteen consecutive days. The athletes wore a CGM for a duration of 10 to 14 days, depending on sensor adhesion. During this period, athletes recorded the timing of their meals, as well as the timing and characteristics of their training sessions. In addition, one standardized training was executed to assess the agreement between CGM and capillary blood glucose concentrations during exercise. Capillary blood glucose samples were also taken in resting condition to assess the agreement between CGM and capillary glucose concentration at rest. The study was conducted between March and May 2023, and was approved by (blinded for review process).

Participants

A total of 16 Para cyclists (hand bikers, tandem cyclists, track and road-race cyclists) competing at the highest (inter)national level were recruited through an ongoing partnership between (blinded for review process). Exclusion criteria were pregnancy, an injury that disrupted the regular training regimen, or diagnosed diabetes mellitus. All participants were informed about the nature and potential risks of the study before

providing their written informed consent, in accordance with the code of ethics of the Declaration of Helsinki.

Study protocol

The 14-day period commenced with the application of the CGM sensor by a researcher according to the manufacturer's instruction. Based on the participants' training schedule, three days (day A, B and C) within the 14-day period were scheduled for a more detailed examination of glycemic control (Figure 6.1A). On day A, participants performed a standardized exercise session in an overnight fasted state and kept a detailed food record for the remainder of the day. Day B was scheduled on a rest day, during which the participants took seven capillary blood glucose samples at home and kept a detailed food record. During day C, which was scheduled on a regular training day, participants followed their normal training schedule and kept a detailed food record. Exercise training data were recorded digitally throughout the 14-day period.

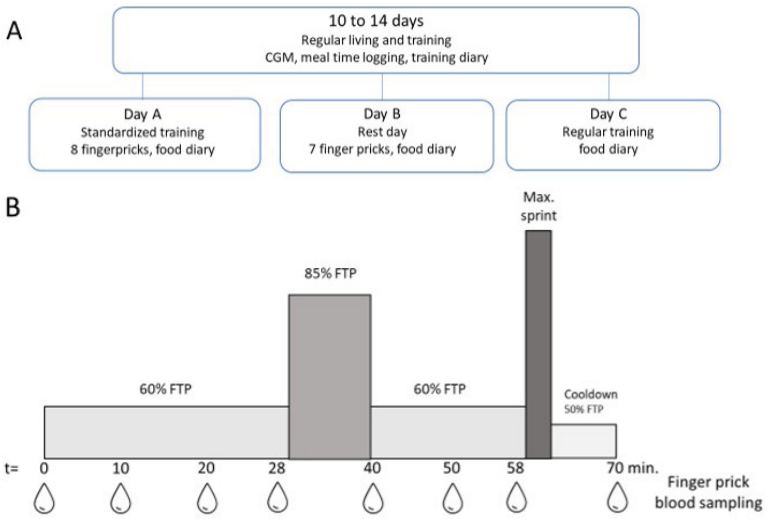

Figure 6.1. Study design. Panel A: Participants wore the CGM sensor for a two-week period (10 to 14 days), while logging the timing of their main meals, and kept a training log. Within the two-week period 3 separate days were planned. On day A, participants performed a standardized exercise session and kept a detailed food record. Day B was scheduled on a rest day, during which the participants took seven capillary blood glucose samples at home and kept a detailed food record. During day C, which was scheduled on a regular training day, participants followed their normal training schedule and kept a detailed food record. Panel B: the standardized training of day A, consisted of (hand)biking for 70 minutes, starting at 60% of the functional threshold power (FTP) for 30 minutes, followed by, 10 minutes at 85% FTP, 20 minutes at 60% FTP, a maximal sprint of

three minutes and a cooldown of 10 minutes at 50% FTP. During the standardized training, eight capillary blood glucose samples were taken by the researchers at T=0, 10, 20, 28, 40, 50, 58, and 70.

Continuous glucose monitoring

Glucose concentrations were measured using an Abbott Libre Sense Glucose Sport Biosensor (Abbott Laboratories, Chicago, IL, US). The sensor was placed on the posterior upper arm, as suggested by the manufacturer. The sensors are equipped with a 4 mm-needle, that penetrates the subcutaneous tissue. Within the interstitial fluid, the CGM sensor operates using a glucose oxidase-soaked electrode at the needle. This enzyme, upon interacting with glucose, produces an electrical current which is calibrated to reflect capillary blood glucose concentrations (21). The predecessors of the Abbott Libre Sense Glucose Sport Biosensor, the Abbott Freestyle Libre and Abbott Freestyle Libre 2, reported a MARD of 11.4% and 9.2% in a diabetic population, respectively (22, 23). The minute-to-minute data from the sensor were accessed and recorded using the SuperSapiens Application (TT1 Products Inc., Atlanta, GA, US), requiring a Bluetooth connection with an NFC-enabled mobile phone. In case the Bluetooth connection was lost, data were temporarily stored on the sensor at 15-min intervals. Participants could upload their data to the SuperSapiens Application by scanning the sensor with the smartphone's NFC chip within 8 hours of the Bluetooth connection being lost.

Capillary blood samples

To assess accuracy, CGM-derived glucose concentrations were compared with capillary blood glucose concentrations measured during a standardized exercise session and in resting conditions. The capillary blood was obtained by a finger prick at the fingertips, and glucose concentrations were measured with the Contour Next One glucose meter (Ascensia Diabetes Care, Parsippany, NJ) with corresponding test strips. The Contour Next glucose meter (the predecessor of the Contour Next One) has been reported as the most accurate self-monitoring blood glucose device available, with a bias of -1.2% and a coefficient of variation (CV) of 5.3% (24). During the standardized exercise session, eight capillary blood samples were taken by a researcher on pre-specified time points during the exercise session (Figure 6.1B). On a designated rest day, (day B; Figure 6.1A), participants collected seven capillary blood samples at home. The samples were taken 5 min before and one hour after each main meal (breakfast, lunch and dinner), as well as immediately before bedtime. During the study instruction, the researchers provided a demonstration

of the finger-pricking procedure, accompanied by written instructions. Participants were instructed to begin by carefully washing and drying their hands. They were then instructed to use the provided lancet device to puncture one of their fingers, discard the initial blood drop, apply the second drop onto the testing strip, and insert it into the Contour Next One device.

Nutritional intake

On three separate days (day A, B and C; Figure 6.1A) during the 14-day period, participants reported their full nutritional intake by means of a food record. Data on timing, products and portion sizes were collected. The dietary records were processed using Compl-eat software (Wageningen University, Division of Human Nutrition) to calculate the intake of energy, carbohydrates, mono- and disaccharides, protein and fat intake for each main meal and over 24 h. On the days without a detailed food record, participants used the SuperSapiens App to digitally log the timing of their main meals, i.e. breakfast, lunch, and dinner. The 2-h postprandial phase after each main meal was analyzed for mean glucose, peak glucose, and time-to-peak glucose.

Exercise

On day A (Figure 6.1A), the participants performed a standardized exercise session in an overnight fasted state. The training session was scheduled to start between 9 and 11am and lasted 70 min. Training load was based on participants' self-reported functional threshold power (FTP). Participants started with 30 min of cycling at 60% FTP, followed by a 10-min block at 85% FTP, a 20 min block at 60% FTP, a 3 min full out sprint, and a 10 min cool-down period at 50% FTP (Figure 6.1B). During this exercise session, eight capillary blood glucose samples were taken by the researchers at T=0, 10, 20, 28, 40, 50, 58, and 70 min. As capillary blood samples were collected from the fingertips, hand bikers were required to stop cycling for ~30 sec to obtain a blood sample.

The Para cyclists used Trainingpeaks software (25) to record all other training sessions throughout the 14-day period. Participants were already familiar with this application. Data on duration, timing, type of exercise and heart rate were collected. Heart rate was measured using participants' personal chest strap heart monitor. In addition, during cycling or hand bike sessions, workload was assessed using participants' personal crank power meters from either SRM (Schoberer Rad Meßtechnik, Jülich, Germany) or Quarq (Quarq, Spearfish, SD, USA). Data on workload were

not collected during other exercise modes, such as wheeling, rowing, swimming, or strength training.

Data analysis

The research team had access to participants' CGM data through the online Supersapiens dashboard application (26). Raw data from this application were downloaded in Excel format. Since the accuracy of CGMs is lower in the first day after application of the sensor (27), the first 24h of data were discarded. The Excel file was configured for automated analysis of glycemic outcomes using the Glyculator 3.0 software (28), employing minute-by-minute data, equating to 1440 data points over a 24-h period. Data gaps resulting from Bluetooth disconnection were filled using linear interpolation, but only for interruptions ≤30 min. Data gaps >30 consecutive min were excluded from the glycemic outcome analysis. Data were analyzed over 24 h, during daytime (6:00 to 23:59), nighttime (00:00 to 5:59), during exercise, and for all 2-h postprandial periods after the initiation of each main meal during the 14-day period. The time spent in glucose zones was assessed by using the following cut-off points (29): severe hypoglycemia (<2.9 mmol/L), hypoglycemia (<3.9 mmol/L), euglycemia (3.9-7.8 mmol/L), hyperglycemia (>7.8 mmol/L) and severe hyperglycemia (>10.0 mmol/L). To calculate the glycemic variability, the coefficient of variation was calculated as the mean divided by the SD. The mean amplitude of glycemic excursions (MAGE) was calculated based on the arithmetic mean of differences between consecutive peaks and nadirs of differences greater than one SD of mean glycemia (30).

To evaluate accuracy, CGM-derived glucose concentrations were compared with capillary blood glucose concentrations. For this purpose, the timing of the capillary blood glucose measurements was synchronized with the corresponding CGM data, which were smoothed by averaging with the preceding and following 3 data points. The mean absolute relative difference (MARD) was calculated as follows: (capillary glucose – CGM glucose) / capillary glucose * 100%. Outliers in MARD were determined as values exceeding the third quartile plus 1.5 * interquartile range (Q3-Q1), according to the box-and-whiskers plot method of Tukey (31). Outliers of the MARD were calculated based on all available data points, but separately for exercise and rest. If a participant had more than two outliers (out of the seven data points for rest or eight data points for exercise), the participant was excluded for the analysis of accuracy.

Normally distributed data were expressed as mean±SD, while non-normally distributed data were expressed as median (Q1 to Q3). Differences in glycemic outcomes between day- and nighttime were analyzed with a paired samples t-test for normally distributed data or a Wilcoxon signed ranks test for non-normally distributed data. Differences in glycemic outcomes between breakfast, lunch and dinner were analyzed with repeated measures ANOVA with Bonferroni correction for normally distributed data, while non-normally distributed data were analyzed with a Friedman's test, with post-hoc Wilcoxon signed ranks test with Bonferroni correction. Differences in glycemic parameters and MARD between subgroups were analyzed with an independent samples t-test for normally distributed data and a Mann-Whitney U test for non-normally distributed data.

Table 6.1. Participant characteristics.

	Total (*n*=13)	Hand bikers (*n*=8)	Cyclists (*n*=5)
Disability (*n*)			
Spinal cord injury	4	4	0
Limb deficiency	4	4	0
Cerebral palsy	2	0	2
Visual impaired	1	0	1
Lower leg nerve damage	1	0	1
Non-disabled / pilot	1	0	1
Sex (male/female)	11/2	7/1	4/1
Age (years)	35±8	36±10	31±6
Height (cm)	177.3±21.7	171.3±29.5	183.2±10.2
Weight (kg)	72.0 (70.0-78.0)	72.0 (65.8-75.8)	73.0 (67.5-92.0)
Mean daily exercise duration (min/day)	120±26	112±28	133±18
Type of exercise training (*n/athlete*)			
Endurance	8.9	8	10.4
Resistance	1.4	1.5	1.2
Other	0.9	1.5	0
Mean training workload endurance (kJ/session)	1194±561	949±396	1623±593[a]

Table 6.1. Participant characteristics. (*continued*)

	Total (*n*=13)	Hand bikers (*n*=8)	Cyclists (*n*=5)
Functional threshold power (W)	260±81	217±68	328±45[b]
Mean heart rate endurance exercise (bpm)	137±11	136±12	138±9

Data is presented as mean±SD or median (IQR). Other training types included: wheeling, swimming and rowing. [a]Significantly different between hand bikers and cyclists *P*=0.048. [b] Significantly different between hand bikers and cyclists *P*=0.008.

RESULTS

Participants

Participants' characteristics are provided in Table 6.1. During data collection, three participants withdrew from the study: two due to issues with connection between the sensor and their mobile phone, and one participant because of a lack of time and commitment. Of the remaining thirteen participants, eight were hand bikers and five were cyclists (including tandem riders). Hand bikers either had a spinal cord injury or a limb deficiency, while cyclists had cerebral palsy, a visual impairment, nerve damage in the lower extremities or no disability (pilot of a visual impaired athlete). Nine of the thirteen athletes participated in the Paris Paralympic games 2024 and won a total of 12 medals (6 gold, 3, silver, 3 bronze). Furthermore, eight athletes were ranked within the top 5 in the 2024 world rankings in their respective categories.

During the 14-day period, most training sessions were hand biking or cycling sessions (79% of the training sessions), with some resistance training (12%) and other types of training (8%) in the form of wheeling, swimming and rowing. Mean daily training duration was comparable between hand bikers and cyclists, although the absolute workload of the hand bike or cycling training sessions was significantly higher for the cyclists (*P*=0.048). The median energy intake was 2768 (2354 to 3784) kcal/day, comprising 373±130 g of carbohydrates, 143 (109 to 151) g of protein and 96 (84 to 125) g of fat. Further dietary intake data for the main meals are provided in Supplemental Table S6.1.

Glycemia over 24 h, and during daytime and nighttime

A full overview of glycemia over 24 h, and during daytime and nighttime is provided in Table 6.2. The median of mean 24-h glucose concentrations was 5.7 (5.6 to 5.8) mmol/L and was higher during daytime (5.9 (5.7 to 6.0) mmol/L) compared with nighttime (4.9 (4.9 to 5.3) mmol/L; P=0.001; Table 6.2). Overall, participants were in the euglycemic range (3.9 to 7.8 mmol/l) for 91% (90 to 94%) of the time. This percentage was higher during nighttime (97% (89 to 97%)) compared with daytime (90% (89 to 92%); P=0.046). This can be ascribed to the higher prevalence of hyperglycemia during daytime (7% (6 to 10%)) compared with nighttime (0.2% (0.1 to 0.2%); P=0.001). Severe hyperglycemia (>10 mmol/L) was uncommon, with a median duration of 0.2% (0.1 to 0.5%) of the 24h period. None of the participants spent any time in severe hyperglycemia during the night. At the other end of the spectrum, 2.1% (1.6 to 3.6%) of the 24-h period was spent in hypoglycemia (<3.9 mmol/L). The relative prevalence of hypoglycemia was higher during nighttime 3.2% (2.4 to 10.5%) compared with daytime (1.4% (1.2 to 2.7%) P=0.001). Figure 6.2 shows that hypoglycemia and severe hypoglycemia during the night were mainly observed in the athletes with SCI (8.2% (3.0 to 37%) and 3.1% (0.7 to 8.0%) of the time, respectively). One of the athletes with SCI even spent 46% of the nighttime in hypoglycemia, with 9.6% of the time being spent in severe hypoglycemia.

Glycemia during exercise

The mean glucose concentration during exercise was 6.3±0.4 mmol/L, with the participants spending 12.7% (8.1 to 33.5%) of the time in (mild) hyperglycemia. However, severe hyperglycemia was uncommon, with a median duration of 0.7% (0.0 to 2.2%) of the time during exercise. Hypoglycemia was nearly absent during exercise with 0.2 (0.0-1.6)% of the time, while severe hypoglycemia was completely absent.

Table 6.2. Markers of glycemia.

	24h period	Daytime	Nighttime	P-value
Mean glucose (mmol/L)	5.7 (5.6-5.8)	5.9 (5.7-6.0)	4.9 (4.9-5.3)	**0.001**
<2.9mmol/L (%time)	0.2 (0.1-0.6)	0.1 (0.0-0.2)	0.6 (0.0-1.9)	**0.033**
<3.9 mmol/L (%time)	2.1 (1.6-3.6)	1.4 (1.2-2.7)	3.2 (2.4-10.5)	**0.001**
3.9-7.8 mmol/L (%time)	90.8 (89.8-93.7)	89.9 (88.5-92.4)	96.5 (89.5-97.3)	**0.046**
>7.8 mmol/L (%time)	5.4 (4.5-7.2)	7.4 (6.0-9.5)	0.2 (0.1-0.2)	**0.001**
>10.0 mmol/L (%time)	0.2 (0.1-0.5)	0.3 (0.1-0.7)	0.0 (0.0-0.0)	**0.002**
MAGE	1.9±0.2	2.0±0.2	1.3±0.2	**<0.001**
CV	20.6±2.6	20.1±2.3	14.8±2.7	**<0.001**
SD	1.2±0.1	1.2±0.1	0.7±0.1	**<0.001**

Data is presented as mean±SD or median (IQR). *P*-value is reported for difference between day- and nighttime.

Table 6.3. Markers of postprandial glycemia

	Breakfast	Lunch	Dinner	P-value
Mean glucose (mmol/L)	6.0±0.5	6.4±0.6	6.1±0.4	**0.004**[a]
<2.9mmol/L (%time)	0.0 (0.0-0.0)	0.0 (0.0-0.0)	0.0 (0.0-0.0)	N.A.
<3.9 mmol/L (%time)	1.3 (0.0-3.3)	0.6 (0.0-2.3)	1.2 (0.0-3.6)	0.442
3.9-7.8 mmol/L (%time)	86.1 (79.7-94.1)	81.3 (74.4-90.0)	90.0 (83.5-96.5)	0.116
>7.8 mmol/L (%time)	7.6 (4.2-14.7)	15.7 (8.7-22.1)	5.9 (2.8-14.5)	**0.037**[b]
>10.0 mmol/L (%time)	0.0 (0.0-0.4)	0.0 (0.0-2.2)	0.0 (0.0-0.4)	0.748
MAGE	1.9±0.5	2.0±0.5	1.6±0.7	0.210
CV	5.8±0.6	6.4±0.6	6.0±0.5	**0.003**[a]
SD	1.0±0.3	1.0±0.2	0.9±0.2	0.322
Individual mean peak glucose (mmol/L)	8.1±0.9	8.4±0.8	7.9±0.7	0.179
Time to peak (min)	46±8	52±14	49±16	0.584

Data are presented as mean±SD or median (IQR). *P*-values of the main effect are presented. [a] significant difference between breakfast and lunch. [b] Significant difference between lunch and dinner. N.A.: statistical test could not be performed because of absence of severe hypoglycemia in the post prandial periods.

Postprandial glycemia

Markers of postprandial glycemia are shown in Table 6.3. The mean glucose concentrations were significantly higher following lunch compared with breakfast (P=0.003), while the time spent in hyperglycemia was significantly higher after lunch compared with dinner (P=0.040). Mild hyperglycemia (>7.8 mmol/L) was relatively common in the postprandial phase, whereas severe hyperglycemia (>10mmol/L) barely occurred. Additionally, mild hypoglycemia (<3.9 mmol/L) had a low prevalence in the postprandial phase, while severe hypoglycemia (<2.9 mmol/L) was completely absent.

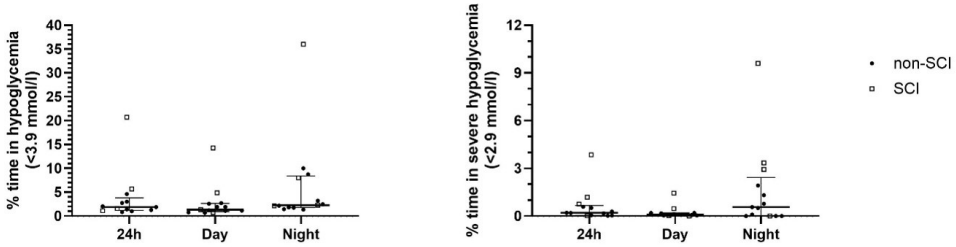

Figure 6.2. Percentage of time spent in hypoglycemia (<3.9 mmol/L) and severe hypoglycemia (<2.9 mmol/L) during 24 h, daytime and nighttime, in participants with and without spinal cord injury as measured with continuous glucose monitoring. Data are presented as median±IQR.

CGM vs capillary blood glucose concentrations

During resting conditions, four (out of 91) matched data points were missing across three participants, attributed to the absence of capillary recordings from these individuals. As shown in Figure 6.3A, the mean glucose concentration assessed over all time points was comparable between capillary blood samples (5.5±0.9 mmol/L) and corresponding CGM-derived samples (5.6±1.2 mmol/L; P=0.484). The MARD was 12±6%, with the Bland-Altman analysis (Figure 6.3D) showing a mean bias of 0.2±0.8 mmol/L with limits of agreement ranging from -1.3 to 1.7 mmol/L. During exercise, seven (out of 104) matched data points were missing across four participants, two due to unsuccessful finger pricks and five due to missing CGM data recordings. The mean capillary blood glucose concentration during the exercise session in the fasted state was 4.8±1.0 mmol/L, while the mean blood glucose concentration of corresponding CGM measurements was 6.3±1.3 mmol/L (P<0.001; Figure 6.3B). The Bland-Altman analysis (Figure 6.3E) revealed a mean bias of 1.5±1.0 mmol/L with limits of agreement ranging from -0.5 to

3.5 mmol/L. This discrepancy was accompanied by a MARD of 34±12%, which was significantly higher compared to the MARD in resting conditions (P<0.001). Moreover, while capillary blood glucose concentrations remained relatively stable during the 60 min exercise session, CGM-derived blood glucose concentrations appeared to rise, leading to an increasing discrepancy between capillary and CGM-derived glucose concentrations over the course of the exercise session. It is interesting to note that the MARD during exercise was substantially higher in hand bikers (41±9%) compared with cyclists (24±11%; P=0.01; Figure 6.3C).

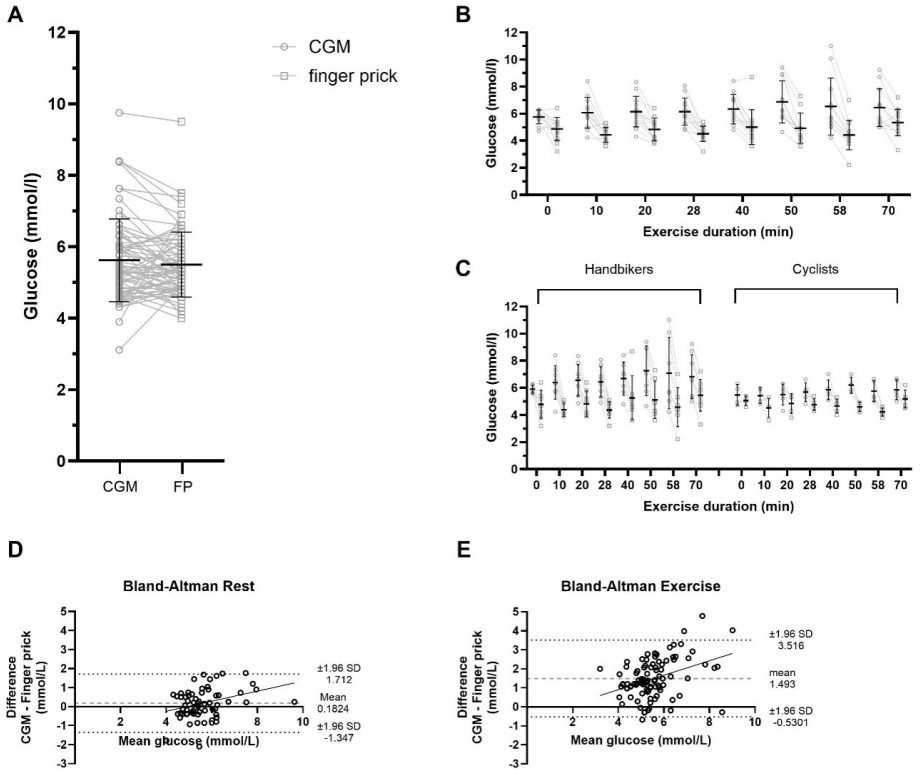

Figure 6.3. Accuracy of CGM during resting and exercise conditions. Blood glucose concentrations of corresponding CGM and capillary measurements assessed during resting conditions (panel A) and over the time during standardized exercise (B). In panel C, blood glucose concentrations during exercise are shown for hand bikers and cyclists separately. Panel D and E represent the Bland-Altman plots of the blood glucose values measured with the CGM and finger prick method during rest (D) and during exercise (E). Data are presented as mean±SD.

DISCUSSION

The current study employed CGM to assess 24-h glycemic control in elite Para cyclists and assessed the accuracy of CGM in both resting and exercise conditions. The study revealed that over the 24-h period, athletes are mainly in euglycemia. Some mild hyperglycemic periods (>7.8 mmol/L) were noted during the daytime, mostly following meals and during exercise, whereas more severe hyperglycemia (>10 mmol/L) was uncommon. Hypoglycemia (<3.9 mmol/L) occurred more frequently at night compared with daytime, although its extent was limited in most athletes. Nevertheless, athletes with SCI seemed to have a higher risk of severe nocturnal hypoglycemia (<2.9 mmol/L). Furthermore, the accuracy of the CGM appeared satisfactory under resting conditions but became compromised during exercise, especially in the case of hand bikers.

Time spent in glycemic ranges

The elite level Para cyclists in our cohort spent 91% of the time in the euglycemic range, which is comparable to the 89% found in elite athletes without a disability (8) and the 93% in a large cohort of healthy active individuals (14). This large proportion of time spent in euglycemia aligns with the expectations for healthy individuals without diabetes, where blood glucose homeostasis is tightly regulated (32). Nevertheless, time spent in euglycemia was somewhat lower than the 96% in a healthy non-athlete population (33). This small discrepancy can be ascribed to the additional time our participants spent in hyperglycemia. Given the mean training duration of two hours per day, alongside the relative increase of hyperglycemia during exercise, the exercise itself appears to be an important factor explaining the variance in time spent outside the euglycemic range. Furthermore, the greater energy expenditure in athletes compared with non-athletes necessitates a higher energy intake. This can be achieved by consuming larger meals which may provoke a greater postprandial glycemic response. Indeed, the athletes in our cohort spent more than one hour a day (5.4% of the time) in hyperglycemia, which is marginally higher than the 2.4 to 3.6% reported in healthy non-athlete populations (14, 33). Although chronic hyperglycemia is a potential negative regulator of aerobic adaptations to exercise (6) and therefore potentially negative for endurance athletes, the minor and mild hyperglycemic episodes observed in the current study are unlikely to hamper endurance exercise adaptations. Indeed, acute hyperglycemia does not affect muscular strength, power or endurance performance in healthy active individuals (34). However, it remains to be established whether

the mild hyperglycemic episodes during exercise observed in the current study affect substrate utilization, as previously reported with hyperglycemic clamping during exercise (7).

The median time spent in hypoglycemia in the current study (2.1%) was comparable to Swedish swimmers (2.6%) (35) and healthy active individuals (3.4%) (14), but noticeably lower than the 8% reported in elite endurance athletes by Flockhart and coworkers (8), although the cut-off point for hypoglycemia was set marginally higher in the latter study. In line with the study of Flockhart *et al.,* hypoglycemic episodes were mainly prevalent during the night, although there was substantial variation between individuals in the severity and duration of hypoglycemia. In this regard, particularly athletes with SCI seemed to be susceptible for nocturnal hypoglycemia. This may be attributed to a diminished counterregulatory response to hypoglycemia in individuals with SCI, stemming from dysregulation of the autonomic nervous system (15). One participant with SCI even spent almost half (46%) of his nights in hypoglycemia. Although severe nocturnal hypoglycemia has been demonstrated to induce an awakening response in healthy individuals (36), it remains unclear whether individuals with SCI experience similar effects on sleep or exhibit an impaired epinephrine and neurogenic response like individuals with diabetes (36). Furthermore, the implications of hypoglycemia-induced impairments in sleep quality for recovery and performance have yet to be determined.

In terms of accuracy, the MARD between capillary and CGM-derived glucose concentration in resting conditions (12%) was comparable with the reported MARD of the Abbott Freestyle Libre and Abbott Freestyle Libre 2 (11.4% and 9.2% respectively) in individuals with diabetes (22, 23). Moreover, the mean bias between capillary and CGM-derived glucose concentrations was only 0.2 mmol/L, with acceptable limits of agreement. Hence, the accuracy of CGM during resting conditions can be considered satisfactory. In contrast, a large discrepancy between CGM and capillary glucose concentrations was noted during exercise (MARD 34%), with a positive bias of 1.5 mmol/L with CGM compared with capillary glucose concentrations. The diminished accuracy of CGM during exercise in athletes without diabetes has also been recently shown by Clavel *et al.* (MARD 13%) (17) and Bauhaus *et al.* (MARD 18 to 22%) (19). However, the MARD during exercise in the current study (34%) was markedly higher compared to previous reports. This discrepancy seems to be mainly attributed to the higher MARD in the hand bikers (41%) compared with

the cyclists (24%) in the current study. When considering the MARD observed in the cyclists alone, results of the current study were in line with the MARD during moderate-intensity cycling exercise (22%) as reported by Bauhaus and coworkers (19). Moreover, while exercise intensity could play a role in the accuracy of CGM during exercise (19), the current study suggests that exercise duration can also affect accuracy. While capillary blood glucose concentrations remained relatively stable during exercise in the fasted state, CGM-derived glucose concentrations increased during exercise, resulting in an increasing discrepancy over the course of the exercise session. In this regard, the longer duration of the exercise session in the current study (70 min) compared with Clavel *et al.* (38 min) and Bauhaus *et al.*, (60 min) may have contributed to the lower accuracy observed in the current study compared with both previous studies. Another difference between the studies is that exercise was performed in a fasted state in the current study, whereas participants in both previous studies exercised in a fed state.

Several mechanisms may contribute to the impaired accuracy of the CGM during exercise. Firstly, CGM sensors react with glucose in the interstitial fluid, where the resulting electrical current is calibrated to reflect capillary blood glucose concentrations (21). Although glucose concentrations in the subcutaneous interstitial fluid and capillary blood are generally closely correlated, both exercise and the associated rise in temperature increase the blood flow and glucose flux in active muscle (37, 38), which likely alters the ratio between local interstitial glucose concentrations and capillary blood glucose concentrations, leading to a reduced CGM accuracy (39). Furthermore, changes in temperature (40) and pH (41) induced by exercise potentially affect the accuracy of CGM by influencing the enzymatic activity of glucose oxidase. Altogether, these factors may also explain the markedly lower accuracy during exercise in hand bikers versus cyclists as observed in the current study. In both groups, the CGM sensors were positioned on the backside of the upper arm. It is evident that the upper arm muscles are more actively engaged in hand biking compared to cycling, which could lead to a higher blood flow, glucose flux, and temperature, and lower pH in the interstitial space surrounding the CGM sensor. Irrespective of the reasons for inaccurate glucose measurements during exercise, the positive bias of CGM-derived glucose concentrations could result in an overestimation of the time spent in hyperglycemia in athletes. Consequently, the greater prevalence of hyperglycemia in elite athletes compared with healthy non-athletes, as reported by Flockhart et. al. (8), may not necessarily reflect an impaired

glucose tolerance, but rather be an artifact due to inaccurate glucose readings during exercise.

Limitations

Some limitations of the current study are important to discuss. Firstly, accuracy of the CGM was assessed against capillary blood glucose concentrations measured by handheld capillary blood glucose monitors. Although the capillary blood glucose monitors used in the current study have been shown to be highly accurate (24), laboratory methods such as photo- or mass spectrometry, which are generally regarded as the gold standard for the assessment of glucose concentrations, could have provided even greater accuracy. Consequently, the reported MARD could be slightly over- or underestimated. It should also be noted that lying on the sensor during sleep can occasionally result in inaccurate glucose readings, likely due to restricted blood flow from tissue compression (42). Although this issue has not been investigated for sensors placed on the posterior upper arm, the possibility of false positive nocturnal hypoglycemic readings cannot be ruled out in the current study. Finally, this study was conducted with a relatively small sample size, particularly in the context of subgroup analyses (i.e. SCI versus non-SCI and hand bikers versus cyclists), potentially resulting in insufficient statistical power for certain subgroup analyses. Despite this limitation, the subgroup analyses highlight important areas for future investigation, specifically regarding the influence of SCI on blood glucose regulation in Para athletes, and the effect of sensor location combined with the type of exercise on the accuracy of CGM during exercise.

CONCLUSIONS

This study demonstrates that blood glucose concentrations of Para cyclists reside within the euglycemic range most of the time. Mild hyperglycemic (>7.8 mmol/L) episodes are commonly experienced by Para cyclists, particularly following meals and during exercise, while severe hyperglycemia (>10 mmol/L) is rarely observed. Mild hypoglycemia (<3.9 mmol/L) occasionally occurs during the night, while severe hypoglycemia (<2.9 mmol/L) is almost exclusively observed in athletes with a SCI, thus warranting attention in this population. While the accuracy of CGM is satisfactory at rest, discrepancies with capillary blood glucose sampling arise during exercise, particularly in hand bikers where CGM sensors were placed in proximity to highly engaged muscle. This underscores the need for caution in interpreting CGM-derived glucose concentrations during exercise.

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SUPPLEMENTAL

Supplemental Table S6.1. Nutritional intake for all meals and at breakfast, lunch and dinner separately.

	Total	Breakfast	Lunch	Dinner	P-value
Energy (kcal)	2768 (2354-3784)	552 (454-802)	757 (577-951)	844 (721-871)	0.061
Carbohydrate (g)	373±130	79±26	81±35	84±22	0.885
Carbohydrate (en%)	47±4	53±8	43±13	42±10	0.139
Mono and disaccharide (g)	110 (76-192)	27 (20-49)	12 (5-31)	13 (11-19)	**0.025**[b]
Protein (g)	143 (109-151)	20 (17-31)	30 (22-42)	42 (39-64)	**<0.001**[bc]
Protein (en%)	17 (16-20)	14 (12-16)	15 (14-19)	24 (17-30)	0.061
Fat (g)	96 (84-125)	20 (12-28)	34 (21-39)	27 (20-41)	0.301
Fat (en%)	32±4	29±8	37±11	32±10	0.307

[b] Significant difference between breakfast and dinner. [c] significant difference between lunch and dinner.

Chapter 7

General discussion

SECTION 1 ENERGY REQUIREMENTS

Adequate energy intake forms the foundation of an athlete's diet (1). For this purpose, a clear understanding of an athlete's energy requirements is essential. When in energy balance, the total daily energy expenditure (TDEE) is the primary determinant of the energy requirements. Accurately assessing TDEE requires precise nutritional counseling, ensuring that dietary recommendations support optimal performance, recovery, and overall health (2).

The daily energy requirements of Paralympic athletes

The most accurate method to assess TDEE is through measurement with the doubly labeled water (DLW) method, which is the golden standard method. While its use in Paralympic cohorts is limited, DLW has been applied in individuals with disabilities. For example, TDEE in non-athletes with spinal cord injury (SCI) has been reported to range from 2340 to 2770 kcal/day, depending on the level of physical activity (3, 4). In non-athletes with transtibial amputation, TDEE was assessed while using two different protheses and found to be between 3100 and 3400 kcal/day (5), which is relatively high for non-athletes. Given the nature of the study, which involved testing different prostheses, participants may have been more physically active than usual. In Paralympic athletes specifically, only two studies to date have used the DLW method, our study (Chapter 2) and the case study by Ellis *et al.* (6). The results from these studies have provided TDEE estimates ranging from 1400 to 5000 kcal/day or 39 to 81 kcal/kg fat-free mass (FFM)/day in Paralympic athletes, highlighting significant variability across sports and individuals. The large range in TDEE was not only attributed to differences in FFM, but also to differences in exercise duration and the presence of spinal cord disorders (SCD), such as spinal cord injury or spina bifida. Similar to athletes without disabilities, TDEE varies significantly across sport disciplines due to differences in body composition and physical activity energy expenditure (PAEE), which tends to be more variable and relatively high in athletic populations. While resting metabolic rate (RMR) is the primary determinant of TDEE in sedentary individuals, PAEE plays a much larger role in athletes and tends to fluctuate throughout the training season of an athlete. Although the doubly labeled water (DLW) method is considered the gold standard for assessing TDEE under free-living conditions, it only provides a snapshot of TDEE within a specific period of the training cycle, raising concerns about its ability to reflect the TDEE throughout the entire year (7). Moreover, DLW cannot differentiate between the in-

dividual components of TDEE, such as RMR or PAEE and does not provide insight into day-to-day variation in TDEE. Additionally, the DLW method is expensive and not always available for every athlete. Therefore, even though DLW is a highly accurate measurement method, sport dietitians or nutritionists largely rely on alternative methods to estimate the TDEE of Paralympic athletes.

Estimating the resting metabolic rate of Paralympic athletes

Because direct measurement of TDEE is not always feasible in practice it is often estimated, starting with an assessment of the RMR. As shown in Chapter 2, RMR accounts an average for 51% of TDEE in Paralympic athletes, making it a critical element in accurately estimating total energy requirements. RMR can be measured directly using indirect calorimetry, typically performed with a ventilated hood. This method has been used in various Paralympic cohorts, such as Para swimmers (8) (1495 kcal/day or 29,1 kcal/kg body mass), wheelchair rugby players (9) (1735 kcal/day or 26 kcal/kg body mass), athletes with SCI (1538 kcal/day or 22 kcal/kg body mass) (10) and in our cohort of Paralympic athletes (Chapter 3). Across these studies, FFM was established as the main determinant of the RMR. This aligns with findings in both individuals without a disability and non-athletes with SCI, where FFM has been reported to explain 70-85% of the variance in RMR (11, 12).

However, even after adjusting for FFM, athletes with SCD had a significantly lower RMR than athletes with other disabilities, which aligns with previous research (13-17). As described in Chapter 1, SCD can lead to a reduction in sympathetic nervous system activity. The inhibition of the SNS can lead to a 4 to 9% decrease in RMR (18-20), which corresponds with the ~100 kcal/day reduction in RMR observed in athletes with SCD as presented in Chapter 3. Therefore, estimating the RMR of Paralympic athletes requires accurate assessment of FFM, while also accounting for the specific impact of the athlete's disability, particularly in cases like SCD where RMR may be lower due to reduced sympathetic nervous system activity. Since measuring RMR is not always possible, prediction equations are necessary. However, current prediction equations are commonly based on athletes without disabilities (21) or on non-athletes with disabilities (22, 23), and thus may not be appropriate for the Paralympic population. For example, standard equations often overestimate RMR in athletes with SCD, and may not account for altered body composition seen in other conditions such as amputation or achondroplasia (24).

For athletes without a disability a decision tree has been developed to determine how to estimate the RMR of the athlete (21). However, no such decision tree has been developed for Paralympic athletes. In Chapter 3, we developed several RMR prediction equations for Paralympic athletes, each based on different input variables. One of the equations included blood levels of triiodothyronine (T3) as a predictor. While this equation showed superior predictive value, it is less practical for routine use, since T3 is not commonly measured. The remaining two equations offer more practical use, differing primarily in whether to use FFM, as measured via dual energy X-ray absorptiometry (DXA), or body mass and sex as predictors. Although the equation using FFM provided slightly better predictive accuracy, the use of body mass and sex may actually be preferred, due to the wider accessibility and reliability of the measurements.

Measuring FFM or using sex and body mass for RMR and TDEE prediction?

Many prediction equations for the TDEE or RMR use FFM for the prediction. However, the practicality of using FFM is questionable. It is important to recognize that the development of the prediction equations are based on measurements of FFM using a specific method. However, various methods can result in different FFM values. In Chapter 4 we demonstrated that skinfold measurements yield a considerable bias in FFM compared to DXA scans. Therefore, even though skinfold measurements are quick, cheap, and easily performed in the field, and are good for keeping track of changes in the body composition of Paralympic athletes, it should not be translated to a FFM value. Moreover, FFM values derived from skinfold measurements should not be used for the prediction of RMR. For the development of prediction equations, DXA scans are frequently used for the assessment of body composition. DXA is considered a highly reliable and accurate method for assessing body composition in athletes (26). One of its advantages is its precision in measuring regional and total body composition, making it particularly useful for athletes with atrophy in the limbs or partly missing limbs. However, DXA scans are expensive and not always accessible in practical settings. In Chapter 3 we showed that predicting the RMR based on body mass and sex achieved nearly the same level of accuracy as estimating the RMR based on FFM. Since the measurement of total body mass is more reliable when using different equipment, we advise to use body mass and sex instead of an estimation of FFM for the prediction of RMR. Therefore, Equation 7.1 is the preferred option for assessing RMR in a Paralympic cohort.

Equation 7.1: RMR prediction

RMR = 489.520 + (14.885 * body mass) - (119.649 * SCD) + (195.999 * sex)

RMR = resting metabolic rate in kcal/day; body mass in kg; SCD = spinal cord disorder, yes = 1, no = 0; sex, male = 1, female = 0.

A practical approach for estimating the daily energy requirements of Paralympic athletes

Once the RMR is established, TDEE can be estimated using several approaches. One method is to apply the prediction developed in Chapter 2. Alternatively, TDEE can be calculated by adding an allowance for physical activity to the RMR. This can be done in two manners. A physical activity level (PAL) value, which represents how active an athlete is throughout the whole day, can be multiplied by the RMR. In the other approach, physical activities performed throughout the day are assigned metabolic equivalent of task (MET) values, which are then used to calculate the energy expenditure for each activity. These are summed and added to the RMR to estimate TDEE. Each method has advantages and limitations, depending on the accuracy of available data and the context in which the estimation is being made.

Option 1: Estimation of TDEE based on Equation 7.2

In addition to direct measurements, predictive estimations have been used to estimate the TDEE of Paralympic athletes (9, 10, 27). Abel *et al.* (27) assessed the energy expenditure during exercise and the basal metabolic rate (BMR) of hand bikers and wheelchair racers. Those values were then combined with an additional 10% to account for the thermic effect of food, resulting in a TDEE estimate of 2100 kcal/day. This value is lower compared to the cohort in Chapter 2, likely because the PAEE of the hand bikers and wheelchair racers only accounted for exercise energy expenditure (EEE) and did not include non-exercise activity energy expenditure. Similarly, Farkas *et al.* (28) estimated the TDEE of non-athletes with SCI to range between 1470 to 1770 kcal/day, depending on the level of lesion. However, their estimation relied on a simple activity correction factor of 1.15 to multiply with the RMR to estimate the TDEE, rather than a direct measurement of PAEE, which may limit its accuracy. In contrast, Chapter 2 describes several prediction equations to directly estimate the TDEE, based on DLW data, that incorporate sport-specific EEE. The following equation showed the highest accuracy:

Equation 7.2: TDEE prediction

TDEE = (RMR + (-861.931 + (30.893 * FFM) + (6.345 * ED) –(266.949 *SCD))) * 1.111

TDEE = total daily energy expenditure in kcal/day; RMR = resting metabolic rate in kcal/day; FFM = fat free mass in kg; ED = exercise duration in minutes/day; SCD = spinal cord disorder (yes = 1; no = 0)

Equation 7.2 was derived from a cohort primarily consisting of Para cyclists, wheelchair basketball players, wheelchair tennis players, Para alpine skiers, and Para cross-country skiers with various disabilities, including spinal cord disorders, neurological conditions, limb deficiencies, visual impairments, or other non-categorized disabilities. It should be noted that this Equation 7.2 has not been validated in other Paralympic cohorts. It is important to consider that other sports or disabilities may lead to different predictions of energy expenditures. One important factor in Equation 7.2 is the training duration, however in our cohort no static wheelchair sports such as fencing or table tennis were included. Therefore, Equation 7.2 might not be suitable for them, because EEE is lower in those sports and, therefore, training duration has less impact on TDEE for those sports. Furthermore, the prediction equation is dependent on measurements or estimations of the RMR, FFM, and training duration of the athlete. In hindsight, a prediction equation that included body mass and sex instead of FFM might have offered greater practical value. Nonetheless, accurately assessing RMR, FFM, and training duration remains essential for reliable prediction of TDEE. This is not always possible, therefore, in practice, the TDEE will commonly be predicted by estimating or measuring the RMR and adding an allowance for the physical activity.

Option 2: TDEE = RMR * PAL

The second common approach to estimate TDEE, involves multiplying the RMR by a PAL factor, the latter quantifies the energy expended through both activities of daily living and exercise energy expenditure. PAL values are used to express the activity level throughout the whole day. PAL values range from 1.4 for sedentary individuals to 2.0 for highly active individuals, with values reaching up to 4.5 for extremely active individuals (Table 7.1). Whitin the Western society a PAL of 1.5-1.6 is considered average (29, 30), while non-disabled athletes and military personnel have demonstrated PAL values exceeding 2.0 (31). The average

PAL value for our Paralympic cohort was 1.9 (Chapter 2), with a wide range from 1.4 to 2.9. The lower end of this range, 1.4 PAL, is below what would typically be expected in elite athletes. These low values can be due to an inactive lifestyle next to training, or a low energy expenditure during daily life activities. At the upper end of the range, a PAL of 2.9 is considered non-sustainable for extended periods and is usually only observed during phases of high volume training in elite athletes (32).

Assessing an individual's PAL requires detailed reporting of daily activities, which can be accomplished through self-report methods such as activity diaries or recall assessments. For individuals with a disability the diaries or recalling methods need to be specific for the disability. For individuals with visual/hearing impairments or locomotor issues the physical activity scale for individuals with physical disabilities (PASIPD) was developed (34). Additionally, the Physical Activity Recall Assessment for People with Spinal Cord Injury (PARA-SCI) was developed specifically for individuals with SCI (35). These tools can be used to provide a quick overview of the physical activities of a Paralympic athlete, which may contribute to making an informed choice for the PAL value. There is no literature available on specific PAL values for people with disabilities. It is, therefore, advised to use the PAL values as described in Table 7.1. It is important to remember that a small deviation in the chosen PAL value, has a major impact on the calculated TDEE. Consequently, it may be better to use a PAL value in combination with an allowance of energy expenditure during specific activities.

Table 7.1. Physical activity level (PAL) values with corresponding lifestyles. Table adapted from FAO/WHO/UNU (33).

Category	Description	PAL-value
Sedentary or light activity lifestyle	Involves minimal physical effort. Mostly sitting, light chores, or occasional movement.	1.4-1.69
Active or moderately active lifestyle	Includes some moderate to vigorous activity daily or jobs that require more movement, like construction work or traditional farming.	1.7-1.99
Vigorous or vigorously active lifestyle	Characterized by regular, intense physical work or exercise for several hours a day, such as manual labor or daily athletic training.	2.0-2.4
Extremely active lifestyle (not sustainable for long periods)	Extremely high PAL (e.g., 4.5) occurs in short-term intense efforts like expedition or competition and isn't sustainable long term.	>2.4

Option 3: TDEE = RMR * PAL + MET

A third approach to estimating TDEE is to multiply the RMR by the PAL while separately adding the energy cost of specific sports or activities using metabolic equivalent of task (MET) values. In this method, sport-specific activities should be excluded from the PAL estimation, resulting in a lower PAL value, but the calculated exercise energy expenditure is subsequently added to the product of RMR and PAL. For individuals without a disability an extensive compendium exists, in which for all sorts of activities the energy expenditure has been measured (36). In this compendium 1 MET equals 3.5 mL of oxygen consumed per kg body weight per min, which represents the energy expenditure during rest. However, conventional MET values may not always be applicable to individuals with disabilities, due to loss of FFM (35), different movement patterns, and assistive devices significantly affecting energy costs.

For wheelchair users the MET compendium by Conger *et al.* (37) provides more appropriate values, with one MET defined as 0.992 kcal/kg/h to compensate for the lower RMR observed in individuals with a disability, mainly in individuals with SCI. This compendium is primarily based on individuals with SCI, and includes limited data from individuals with other disabilities. For athletes with SCI who are wheelchair dependent it is advised to use this compendium for the MET values. Additionally, due to a lack of knowledge for wheelchair users with other disabilities, it is also advised to use this compendium. However, it is important to keep in mind that the energy expenditure and, therefore, MET values, for non SCI individuals can be slightly higher than reported in the compendium.

For individuals who walk with a prosthesis or have an adapted gait, the energy cost for ambulation is generally higher compared to individuals without a disability (38). A transtibial amputee uses 25% more oxygen during treadmill or free walking with a prosthesis, whereas a transfemoral amputee has a 55-65% greater VO_2 uptake compared to individuals without a disability (39). Although no specific MET compendium exists for individuals with adapted gait, with or without prosthesis, it is advised to use the general MET compendium by Herrman *et al.* (40), with adjustments for walking activities. The energy cost for walking needs to be increased with 25% for transtibial amputees and 55-65% for transfemoral amputees. For running activities performed with a sport specific prosthesis, no adjustment is necessary, as these devices are relatively energy efficient and the energy cost of running is comparable to athletes without a disability (41). In cases where an athlete has an adapted gait

without using a prosthesis, the additional energy cost should be evaluated individually, depending on the type and extent of the impairment.

Similarly, for individuals with a visual impairment no separate compendium exists, while their energy expenditure during various activities may require extra energy to perform (42). Visual input normally aids in the planning and correct execution of motor tasks. Visually impaired individuals must rely on other senses, such as hearing, touch, and proprioception to execute motor tasks. This leads visually impaired individuals to make shorter strides during both walking (43) and running (44), which decreases locomotion efficiency and increases energy expenditure (42). Therefore, MET values for the general population may be too low for the visually impaired population. However, since there is no specific MET compendium for this group, it is still advised to use the compendium by Herrmann *et al.* (40) but keep in mind that certain activities might be more energy demanding due to the disability.

Examples of estimating the energy requirements of a Paralympic athlete

Based on the three described options to estimate TDEE, two cases are presented on page 174 and 175 to illustrate their application. For both athletes, the RMR was first estimated using Equation 7.1, which relies on body mass and sex. In Option 1, TDEE was estimated using Equation 7.2, which requires FFM. FFM was obtained from a DXA scan. Equation 7.2 also includes variables such as exercise duration, presence of SCD, and sex. In Option 2, TDEE was estimated by multiplying the RMR by a PAL value. A relatively high PAL was chosen due to the athletes' substantial training hours. In Option 3, the PAL was estimated to be lower because training was accounted for separately using MET values instead of being included in the PAL. MET values were taken from Herrman *et al.* (40) for Case 1 and Conger *et al.* (37) for Case 2. For the Paracyclists, the MET value for cycling at 30 km/h was used, and for the wheelchair tennis player the MET value for wheelchair tennis was used.

Both athlete's TDEE was also measured using the DLW method. When comparing the DLW results with three estimation options, option 2 and option 3 were the most accurate for case 1 and 2 respectively. However, it is clear that choosing a slightly different PAL value would lead to significantly different TDEE values. These examples highlight that while all three options provide a general indication of TDEE, an accurate estimation of PAEE is essential to provide a more precise TDEE estimate.

Estimating the physical activity energy expenditure with wearables?

Based on previous research and our study in Chapter 3, we are now able to make a relatively accurate estimation of the RMR of a Paralympic athlete. However, as revealed in the example cases, for a good estimation of the TDEE an accurate estimation of the PAEE is required, especially among athletes, due to their high PAL. We already discussed three separate options to estimate the TDEE based on the RMR with an activity factor. However, measuring the PAEE objectively would be prefered. More specifically, an objective measurement of the physical activity, with information about the frequency, duration, and intensity of the activities performed over a longer period of time, with minimal discomfort for the athlete, would be ideal. Wearables like accelerometers can perform such objective measurements (45) and are more reliable and valid compared to self-report methods, such as questionnaires (46). However, currently, data on PAEE derived from accelerometers rely on algorithms created for individuals without disabilities, while movement patterns of athletes with a disability, especially wheelchair athletes, can differ significantly. Additionally, the accuracy depends on proper sensor placement (47). Although there is some limited research on sensor placement in individuals with a disability (35, 48), this has not been performed in Paralympic athletes. Combining accelerometry with physiological data, such as heart rate, may enhance accuracy (49), though this requires individual calibration in athletes with autonomic dysfunction. Future research should focus on developing tailored algorithms, refining sensor placement strategies, and validating integration of physiological data with accelerometry data, to improve PAEE and, therefore, TDEE estimation in this diverse population.

Case 1
Sex: male
Body mass: 71.1 kg
FFM = 61.4 kg
Sport: Paracyclist
Training hours: 13 hours per week
Disability: nerve damage, non-wheelchair user

Option 1: direct prediction
RMR = 489.520 + (14.885 x 71.1) – (119.649 x 0) + (195.999 x 1) = 1744 kcal/day
Exercise duration = 13 / 7 * 60 = 111 min/day
TDEE = (1744 + (-861.931 + (30.893 * 61.4) + (6.345 * 111) – (266.949 * 0))) * 1.111 = 3874 kcal/day

Option 2: Prediction RMR * PAL
RMR = 489.520 + (14.885 x 71.1) – (119.649 x 0) + (195.999 x 1) = 1744 kcal/day
Estimation of PAL = 2.3 (due to the 13 h of training a week)
TDEE = 1744 * 2.3 = 4011 kcal/day

Option 3: Prediction RMR * PAL + MET
RMR = 489.520 + (14.885 x 71.1) – (119.649 x 0) + (195.999 x 1) = 1744 kcal/day
Estimation of PAL (without training) = 1.7
MET value for cycling around 30 km/h = 12
MET = 12 * 71.1 * (13 / 7) = 1585 kcal/day
TDEE = ((1744 * 1.7) / 24 * (24-(8/7))) + 1585 = 4320 kcal/day

TDEE measured with DLW = 4111 kcal/day
RMR measured with ventilated hood = 1694 kcal/day

Case 2
Sex: male
Body mass: 67.7 kg
FFM = 56.0 kg
Sport: wheelchair tennis
Training hours: 12 hours per week
Disability: spinal cord injury, wheelchair user

Option 1: direct prediction
RMR = 489.520 + (14.885 x 67.7) – (119.649 x 1) + (195.999 x 1) = 1574 kcal/day
Exercise duration = 12 / 7 * 60 = 103 min/day
TDEE = (1574 + (-861.931 + (30.893 * 55) + (6.345 * 214) – (266.949 * 1))) * 1.111 = 3141 kcal/day

Option 2: Prediction RMR * PAL
RMR = 489.520 + (14.885 x 67.7) – (119.649 x 1) + (195.999 x 1) = 1574 kcal/day
Estimation of PAL = 2.1 (due to the 12 h of training a week)
TDEE = 1574 * 2.1 = 3305 kcal/day

Option 3: Prediction RMR * PAL + MET
RMR = 489.520 + (14.885 x 67.7) – (119.649 x 1) + (195.999 x 1) = 1574 kcal/day
Estimation of PAL (without training) = 1.7
MET value for wheelchair tennis = 4.1
MET = 4.1 * 67.7 * (12 / 7) = 476 kcal/day
TDEE = ((1574 * 1.7) / 24 * (24-(12/7))) + 476 = 2960 kcal/day

TDEE measured with DLW = 2969 kcal/day
RMR measured with ventilated hood = 1554 kcal/day

SECTION 2 ENERGY AVAILABILITY

Could low energy availability be a problem in Paralympic athletes?

Low energy availability (LEA) is described as inadequate energy intake relative to exercise energy expenditure (50), leaving inadequate energy to support normal physiological functions after accounting for the energy cost of exercise. Energy availability is calculated as the energy remaining after subtracting the EEE from the energy intake, relative to the FFM (Equation 7.3). It has been proposed that chronic or prolonged LEA causes a broader syndrome called relative energy deficiency in sports (REDs) which affects multiple bodily functions, such as immunity, reproductive function, and metabolic function, and leads to decreases in performance and health (50). In athletes without a disability, LEA often results from low energy intake, high exercise energy expenditure, or a combination of both. These risk factors also apply to Paralympic athletes, but their impact may differ due to the nature of the athlete's disability. Therefore, we will discuss the various factors influencing the risk for low energy intake and high energy expenditure in Paralympic athletes, to assess if the risk for LEA could be present in Paralympic athletes.

Equation 7.3. Theoretical concept to calculate the energy availability per kg fat free mass.

Energy availability = (energy intake – exercise energy expenditure) / fat free mass

Exercise energy expenditure

Because LEA is calculated as energy intake minus EEE, a high EEE can be a risk factor for LEA, when it cannot be matched by energy intake. As mentioned in Chapter 1 and section 1 of this discussion, there are multiple reasons to assume that the TDEE and the EEE might differ in Paralympic athletes compared to athletes without a disability, of which a key determinant is the difference in FFM. For example, EEE has been reported to be 26 to 85% lower when compared to non-Paralympic sports, with the greater difference in energy expenditure in athletes with tetraplegia or those participating in static wheelchair sports (51). As described in Chapter 2 the energy expenditure of Paralympic athletes differs between sports and disabilities, with PAL values ranging from 1.4 to 2.9 (average 1.9 PAL). Nevertheless, several Paralympic athletes had average TDEE values of 4000 kcal/day measured over a 14-day period. Given the day-

to-day variation in TDEE due to daily variations in EEE, it is likely that on some days TDEE may even exceed 5000 or even 6000 kcal in several athletes. In this regard, Taylor *et al.* (52) found that in elite road cyclists, a 1000 kcal increase in EEE was accompanied by only a 210 kcal increase in EI. This indicates that days with high energy expenditures are hard to fuel, which potentially increases the risk for LEA. Therefore, similar to athletes without a disability, Paralympic athletes with a high energy expenditure, who might not be able to fuel these energy demands, may be at risk for LEA.

Factors influencing the energy intake of Paralympic athletes

The main factor driving LEA is an inadequate energy intake. There are various reasons why an athlete's energy intake may be insufficient to meet their energy demands, often influenced by strong internal and external pressures to optimize performance (50). Factors such as body image concerns, external expectations, or limited nutritional knowledge can contribute to low energy intake and are also observed among Paralympic athletes (2, 53). In addition, disability-specific factors may further impact their energy consumption. Understanding the underlying reasons for low energy intake is essential in evaluating the risk of LEA in Paralympic athletes.

Eating disorders

Eating disorders can significantly impact an athlete's energy intake. For example, anorexia nervosa is associated with markedly reduced energy intake, while binge eating disorders can increase energy intake. Among athletes without a disability the prevalence for eating disorders ranges from 0 to 19 % for male athletes and 6-45 % in female athletes (54). Many athletes are susceptible for eating disorders due to psychological factors such as stress, anxiety and depression (55). Additionally, sports which emphasize leanness (i.e. aesthetic, endurance, and weight-class sports) or coaches focusing on body mass, can cause body image anxiety (54), which increases the risk for eating disorders. A previous study on the prevalence of eating disorders among Paralympic athletes found only 3.1% had a self-reported history with an eating disorder (56), although the specific disorders were not identified. However, when using the eating disorder examination questionnaire (EDE-Q) to evaluate the risk for an eating disorder, more than 30% of the Paralympic athletes reported an elevated score. Additionally, Brook et al. (56) reported that 61.5% of Paralympic athletes had attempted to change their body composition or weight. Pritchett *et al*. (57) reported that 78% of female Paralympic ath-

letes restricted the calorie intake due to discomfort before activity (44%) or concerns about fitting into racing chair or prosthesis (33%). This is in line with Canadian athletes with SCI competing in wheelchair sports who reportedly restrict or monitor their food intake to maintain an ideal body weight for elite sport competition (2). These studies underline that Paralympic athletes may worry about body composition for different or additional reasons compared to athletes without a disability. However, it is not clear if these body image problems, and a possibly elevated EDE-Q score, are accompanied by an inadequate energy intake in Paralympic athletes.

SCI and wheelchair use

Gastrointestinal problems are common among individuals with SCI or wheelchair dependent individuals (58). Bowel and gastrointestinal stress can lead to lower nutritional intake. Indeed 80% of individuals with SCI coinciding with chronic gastrointestinal problems reported to restrict their diet (58). Furthermore, delayed gastric emptying is present in the majority of people with SCI (59) and can lead to an increase in satiety and subsequent lower energy intake (60). Additionally, for athletes in a wheelchair or athletes who make use of a stoma or catheter, bathroom accessibility is an important factor to keep in mind. Wheelchair athletes consciously or unconsciously sometimes choose not to consume snacks or drinks to avoid bathroom trips (61), which lowers the frequency of food and drink intake and, as such, energy intake.

Motor, intellectual, and visual impairments

For athletes with severe cerebral palsy (CP) who also suffer from oral motor dysfunction, the risk for low energy intake is high, due to swallowing difficulties. Indeed, feeding difficulties are present in 30–40% of children with CP, which contributes to inadequacies in nutritional intake (62). However, there is no literature on the prevalence of swallowing difficulties in Paralympic athletes. Additionally, athletes with CP sometimes suffer from intellectual disabilities. Intellectual disabilities can lead to unawareness of dietary needs and potential under fueling (63) or higher consumption of fast food, leading to an increased energy intake. Therefore, proper nutritional counseling is extra important for this group. Additionally, visually impaired individuals find shopping, meal preparation, and restaurant use very difficult (64). This may lead to a lower energy intake in visually impaired athletes, similarly to the older visually impaired population (65).

Collectively, some disabilities of Paralympic athletes may alter the energy intake in these individuals. Some factors increase the risk for low energy intake, while others may increase the risk for high energy intake. In Chapter 2 we assessed the energy intake of Paralympic athletes. We reported multiple Paralympic athletes with an energy intake below their measured RMR, those athletes could become at risk for LEA. However, this finding must be interpreted with caution, as it may reflect underreporting rather than truly inadequate energy intake. In conclusion, Paralympic athletes may experience varying combinations of energy intake and energy expenditure, with some exhibiting high risks for low energy intake and or high energy expenditure. Consequently, individual athletes may face different levels of risk for developing LEA and subsequently REDs.

Assessment of LEA and REDs in Paralympic athletes.

Sport dieticians or nutritionists play a critical role in guiding athletes toward optimal nutrition to support both health and performance. LEA and following that REDs can be majorly disruptive of both health and performance. It is, therefore, important to recognize the signs of LEA and REDs and treat it early on. Traditionally, LEA has been calculated using Equation 7.3, with a threshold for LEA at 30 kcal/ kg FFM (66). However, accurately assessing energy intake, EEE, and FFM is challenging. In Chapter 2 we demonstrated an underreporting of 19% in energy intake, which is consistent with findings from previous nutrition studies (67). Notably, the range of underreporting extended up to 67% in our study, making a reliable LEA assessment using Equation 7.3 impossible. Moreover, assessing EEE often requires indirect calorimetry, which is not always feasible in practice. While calculations of EEE using MET values offer an alternative, they also have limitations, especially in the Paralympic population, as discussed in Section 1 of this discussion. Furthermore, since energy intake, EEE, and FFM are all sensitive to the methods used for their assessment, Equation 7.3 and the fixed threshold lacked practical utility. Therefore, the latest 2023 IOC consensus paper on REDs abandoned the specific cut-off values for LEA and now the most important step for the stratification for the risk of REDS is assessing the presence of various indicators (50). The indicators are divided into severe primary indicators, primary indicators, secondary indicators and potential indicators. Based on the severe primary, primary, and secondary indicators outlined in Table 7.2, the risk of REDs can be assessed. The more severe-indicators are supported by stronger scientific evidence linking them to REDs.

Table 7.2. The severe primary, primary, and secondary indicators for the assessment of the risk for REDs Adapted from the IOC consensus paper (50).

Classification	Indicator	Description
Severe primary indicators (counts as two primary indicators)	Primary amenorrhea	Failure to reach menarche by age 15 with secondary sexual characteristics, or by age 14 years without secondary sexual characteristics
	Prolonged secondary amenorrhea	Absence of ≥12 consecutive menstrual cycles
	Clinically low free or total testosterone	Below the laboratory and age-specific reference range
Primary	Secondary amenorrhea	Absence of 3 to 11 consecutive menstrual cycles
	Sub-clinically low or free testosterone	Within the lowest quartile of the laboratory and age-specific reference range
	(Sub-)clinically low total or free T3	Within or below the lowest quartile of the laboratory and age-specific reference range
	History of ≥1 high-risk or ≥2 low-risk BSI	Within the past 2 years, or ≥6 months of absence from training due to BSI High-risk is a BSI at femoral neck or total hip, sacrum, pelvis Low-risk is a BSI in any other location
	Low BMD Z-score or decrease in BMD Z-score	Z-score < -1 at lumbar spine, total hip, or femoral neck, or a decrease from prior testing (use pediatric norms for <20 yrs)
	Deviation from previous growth trajectory	Change in expected height or weight development
	Elevated EDE-Q score and/or clinical ED diagnosis	EDE-Q global score >2.30 in females, >1.68 in males, or DSM-5-TR diagnosed eating disorder
Secondary	Oligomenorrhea	>35 days between periods for a maximum of 8 periods/year
	History of 1 low-risk BSI or <6 months of absence from training due to BSI	Within the past 2 years See above for classification of low-risk BSI
	Elevated total or LDL cholesterol	Above the reference range
	Clinically diagnosed depression or anxiety	Formal diagnosis from a medical or psychological professional

BSI = Bone stress injury; BMD = bone mineral density; EDE-Q = eating disorder examination questionnaire.

Depending on how many (severe) primary or secondary indicators (Table 7.2) are present in the athlete, the severity or risk for REDs is categorized, as shown in Table 7.3. If an athlete scores a mild risk or higher, treatment, monitoring, and a change in training or competition strategy might be necessary, depending on the severity of the symptoms of REDs. However, it is important to recognize that various indicators used for diagnosing the risk for REDs are potentially affected by the disabilities of Paralympic athletes, either directly or indirectly. This section will discuss these indicators and how different disabilities impact their interpretation.

Table 7.3. The scoring for the assessment of the severity and/or risk for REDs. Adapted from the IOC consensus paper (50).

Severity/Risk	Scoring	Treatment, training and competition recommendations
None to very low	No primary indicators AND ≤ 1 secondary indicator	- No treatment required. - Full training and competition clearance.
Mild	0 primary & ≥ 2 secondary indicators OR 1 primary & ≤ 2 secondary indicators OR 2 primary & ≤ 1 secondary indicators	- Treatment, monitoring and regular follow-up at appropriate intervals. - Full training and competition.
Moderate to high	1 primary & ≥ 3 secondary indicators OR 2 primary & ≥ 2 secondary indicators OR 3 primary & ≤ 1 secondary indicators	- Treatment, close monitoring and follow-up required (e.g., ~monthly) - Some aspects of training and/or competition may need to be modified.
Very High to extreme	3 primary & ≥ 2 secondary indicators OR ≥ 4 primary indicators	- Immediate treatment (± hospitalization) required by frequent monitoring at ~daily to monthly intervals depending on severity. - Significant training and competition modifications required, and in the majority of cases, removal from all training and competition is indicated.

Severe primary indicators

Menstrual function

Menstrual dysfunction is a severe primary indicator of LEA in women (50) and has long been recognized as a symptom of REDs. In times of energy deficit, the body prioritizes bodily functions necessary to survive over bodily functions necessary to reproduce. Therefore, amenorrhea can indicate the body experiencing prolonged energy deficits. However, menstrual irregularities may also result from particular disabilities experienced by Paralympic athletes. Given this, it is important to distinguish between the symptoms of LEA and the consequences of the disability to assess the risk of REDs. Firstly, SCI may influence the hypothalamic-pituitary axis in the acute phase after injury, which influences the menstrual cycle, with many women experiencing secondary amenorrhea directly after the injury (68). Even though the hypothalamic-pituitary-ovarian axis might still be affected in the chronic phase of SCI, research indicates no long-term effects on the menstrual function or reproductive health (68). Normal menstruation typically resumes in an average of 3–5 months following injury (69, 70). It is unlikely that individuals with SCI start Paralympic sports within 5 months after their injury. Therefore, it can be assumed that the secondary amenorrhea is resolved by the time the individual becomes a Paralympic athlete and menstrual function has resumed as before the injury. Furthermore, individuals with SCI are expected to go into menopause around the same age as females without SCI (71). Regarding individuals with CP, research on menstrual function is limited, although one study reported that 29.4% of adolescents with CP experienced menstrual dysfunction. Additionally, later onset of menarche was common in adolescents with CP, with an average age of 15 years compared with 13 years in the general female population (72). Similarly, there is little research on menstrual function in individuals with short stature. However, one study reported that women with achondroplasia tend to experience premature menopause, women with osteogenesis imperfecta reported a late menarche, and women with pseudo achondroplasia and cartilage hair hypoplasia experienced prolonged menstrual cycles (73). These findings, however, have not been widely confirmed by other studies. For athletes with limb deficiencies or visual impairments, no disturbances in menstrual function are expected. In conclusion, menstrual dysfunction can be used as an indicator for the risk of REDs in Paralympic athletes with SCI, limb deficiencies, and visual impairments. Only with CP and short stature there are reasons to be cautious with interpreting menstrual dysfunction. For these disabilities, there is a pos-

sible delated onset of menarche and earlier onset of menopause, which could lead to a false positive for the severe primary indicators of LEA. Furthermore, as mentioned in the consensus statement (50), menstrual cycle indicators cannot be accurately assessed in athletes who are taking sex hormone altering medications (e.g., hormone-based contraceptives). Hormonal contraception changes the menstrual function exogenously, by adding estrogen and or progestin (synthetic progesterone). In previous research 67% of Paralympic athletes reported the use of some form of hormonal contraception (57). Therefore, for the majority of the female Paralympic population the menstrual cycle cannot be used as an indicator for the risk of REDs.

Testosterone

Similar to women, the male body also prioritizes bodily functions necessary to survive over functions necessary to reproduce. Previous research indicated that, although positive for male reproductive function, a high testosterone phenotype is energetically expensive (74). Therefore, low testosterone levels are considered an indicator of LEA. However, disabilities can also alter testosterone levels. Firstly, testosterone deficiency is common among males with SCI, with 40-65% of men with chronic SCI presenting with low testosterone levels (75). This is likely due to disruption of the hypothalamic–pituitary–gonadal axis, which regulates testosterone production. Additionally, hyperprolactinemia, specifically prevalent in individuals with injuries above T11 (76), further contributes to testosterone suppression. For individuals with CP there is some literature suggesting puberty can be delayed in individuals with CP (77), which affects testosterone production. Conversely, altered hormone production may also influence the onset of puberty. Additionally, one study found a 20% prevalence of hypogonadism in adults with CP (78). However, no evidence exists for altered testosterone levels in adults with CP. During adolescence of males with short-stature, short-term testosterone treatment is sometimes used to increase growth, especially if puberty has not commenced after age 13 or 14 (79). Due to the exogenous administration of testosterone, testosterone levels should not be used as an indicator for the risk of REDS in those individuals. However, the most common form of short stature in the Paralympic cohort is achondroplasia, and is not caused by a deficiency in growth hormones or testosterone. Individuals with achondroplasia are usually not treated with exogenous testosterone and endocrine dysfunction has a low prevalence in the adult achondroplasia population (80). Furthermore, there is no reason to assume irregularities of testosterone levels in limb deficiency and visual impair-

ment. Overall, testosterone levels should not be used as an indicator for LEA in athletes with SCI and likely not in those with other spinal cord disorders such as spina bifida. Additionally, in athletes with CP, it should only be used as an indicator when it is confirmed that hypogonadism is not present. For athletes with visual impairment, limb deficiencies, or short stature without testosterone treatment (e.g. achondroplasia) there is no reason to assume it cannot be used as an indicator.

Primary indicators

Triiodothyronine (T3)

For both men and women low total or free T3 is considered a primary indicator of LEA. In short, the hypothalamus is sensitive to external stimuli such as feeding. When fed, the hypothalamus will secrete thyrotropin-releasing hormone, which acts on the pituitary gland and increases the output of thyroid-stimulating hormone. This increases the release of thyroxin (T4) and a small amount of T3 from the thyroid gland. In addition the liver and kidneys convert a part of T4 into T3, supplying roughly 80% of the circulating T3 (81). The thyroid hormones stimulate metabolism, and heat production for thermogenesis (82). By decreasing the T3 and other thyroid hormone levels, the body conserves energy. The disabilities of Paralympic athletes might also influence the T3 levels. Firstly, for individuals with SCI, studies indicate T3, T4, and TSH levels are generally within the normal range (68). For individuals with CP, T3 levels seem to reside within the normal range, due to the thyroid gland being resilient to the causes of CP, namely, anoxia or ischemia in the brain (83). Contrary, short stature can sometimes be related to disruptions in growth hormones, such as IGF-1. Since growth hormones can interact with the endocrine system, they may also influence thyroid function, including the levels of T3. However, the most common form of short stature, achondroplasia, is not typically caused by hormone imbalances. Instead, it is the result from a genetic mutation in the FGFR3 gene, which affects bone growth. Because of this, achondroplasia is generally not associated with abnormal T3 levels. Similarly, for limb deficiencies or visual impairments no deviations in T3 levels are expected. Overall, no irregularities in T3 levels are expected in Paralympic athletes with SCD, CP, achondroplasia, visual impairment, or limb deficiencies. For other short stature disabilities, it is important to confirm that this is not caused by low growth factor levels. Furthermore, pituitary dysfunction is common within the regular population, with a prevalence of 3% of hypothyroidism in Europe (84). It should, therefore, be assured that low

T3 levels are not caused by a dysfunctional thyroid gland, before using it as an indicator for the risk of REDs.

Bone mineral density

A Low bone mineral density (BMD) Z score of <-1.0 at the lumbar spine, total hip or femoral neck is considered a primary indicator for LEA (50). Besides LEA, BMD is also strongly influenced by mechanical loading, which varies among Paralympic athletes based on their mobility and sport-specific demands. It is important to consider the impact of different disabilities on BMD to make an informed decision about using BMD scores for the assessment of LEA. Wheelchair users experience reduced impact forces on the lower body, contributing to lower BMD values at the total hip and femoral neck, as outlined in Chapter 5. Indeed, research in the general population of SCI indicates a high prevalence of osteoporosis at the femoral neck, characterized by a significant decrease in BMD within the first six months post-injury, followed by stabilization (85). In contrast, lumbar spine BMD Z-scores may increase slightly over time (85). This site-specific increase in BMD Z-scores is likely influenced by sport specific loading. As reported in Chapter 5, wheelchair sports with rotational trunk movements increase the BMD of the spine, likely by mechanical loading of the spine. Similarly to individuals with SCI, children with spina bifida exhibit a high prevalence of low BMD at the femoral neck (86). In individuals with CP, ambulatory status plays a critical role in bone health, with wheelchair users demonstrating significantly lower BMD compared to those who can ambulate (87). Specifically, BMD Z-scores at the hip are typically <-1.0 in non-ambulatory individuals, while lumbar spine Z-scores are also <-1.0, except in those with dyskinetic ambulatory CP, where the average Z-score is -0.1 (87). For individuals with unilateral limb loss, Royer and Koenig (88) noted that proximal tibia and femoral neck BMD values were significantly lower in the leg affected by limb loss than in the native leg. Finally, research on individuals with short stature, particularly those with achondroplasia, indicates lower BMD values compared to controls on whole body level and individual body segments (89). Additionally the average BMD Z-score of the lumbar spine in achondroplasia patients was -1.1 (90). While the mechanisms of impaired bone health in achondroplasia is unclear, it has been hypothesized that bone suppression and remodeling associated with the condition contribute to the decreased BMD (2). In conclusion, BMD at the hip is often low in wheelchair using Paralympic athletes and athletes with a prosthesis due to reduced weight-bearing activity. It can be assumed that the loading pattern related to the disability has a more

defined impact on BMD compared to LEA. More research is necessary to assess whether BMD of Paralympic athletes is also associated with LEA. Therefore, whenever the loading patterns of the lower body are not similar to athletes without a disability, due to a difference in ambulation, the BMD Z-scores of the lower body should not be used as an indicator for LEA. Additionally, the lumbar spine BMD Z-scores can be increased in wheelchair sports with rotational movements of the trunk (Chapter 5), and should be excluded as an indicator. For the whole body and upper body BMD Z-scores there are no clear cut off values for LEA yet and can therefore also not be used as an indicator. Since BMD values typically stabilize over time, tracking changes in BMD can be useful for athletes who use wheelchairs or protheses. Similar as with athletes without disabilities, a decline in BMD beyond what is expected for age may be used as an indicator for the presence of LEA. For athletes who have loading patterns similar to athletes without a disability, there is no contraindication for the use of BMD as indicator of LEA.

Bone stress injuries

A bone stress injury (BSI) is an overuse injury, where repetitive load leads to microscopic cracks in the bone, which can progress to a stress fracture if not properly managed. It occurs when bone is unable to withstand repetitive mechanical loading, leading to structural fatigue, progressing into stress fractures or in severe cases, complete fractures (91). The underlying pathophysiology involves cyclic loading that induces microtrauma, which accumulates over time when recovery is insufficient (92). BSIs can occur even in athletes with normal BMD if the mechanical load exceeds the bone's adaptive capacity. However, individuals with impaired BMD, such as those affected by LEA are at heightened risk, as their bones are less capable of withstanding repetitive stress. For the assessment of the risk for REDs, BSI at the femoral neck or total hip, sacrum or pelvis are considered high risk BSI's in the athlete population without disabilities, whereas a BSI at any other anatomical region is considered a low risk BSI. As mentioned in the previous paragraph, in wheelchair dependent athletes the BMD is typically low in non-weight bearing regions such as the femoral neck and total hip, due to limited mechanical loading. The low BMD at the hip could predispose to high risk BSIs, but as these areas are not subjected to repetitive loading in this population, the actual incidence of BSIs in these high-risk locations remains low. Instead, BSI's in wheelchair users are predominantly observed in the upper body, specifically the hand, wrist, rib, or spine, accounting for approximately 90% of BSIs (92). In contrast, ambulatory

Paralympic athletes, with or without assistive devices, are more likely to sustain a BSI in the lower body (68% of BSI's) like, foot, ankle, or tibia (92). Therefore, the classification of high risk BSIs vs low risk BSIs might not be suitable for athletes who are wheelchair dependent. In conclusion, BSIs are prevalent in Paralympic athletes and there is no indication to not use their prevalence as an indicator for the risk of REDs. However, BSIs tend to occur in different locations in Paralympic athletes, compared to athletes without disabilities, especially in wheelchair athletes. Therefore, distinguishing between high and low risk BSI sites may not be appropriate for this population.

Eating disorders

Eating disorders are linked to LEA, with the EDE-Q commonly used to assess the risk for an eating disorder. However, the effectiveness of the EDE-Q outcome as an indicator for the risk of REDs is questionable for the Paralympic population. Over 30% of Paralympic athletes scored high on the EDE-Q, suggesting a high risk for eating disorders. However, within the EDE-Q multiple questions relate to body image, for example: "How dissatisfied have you been with your shape?". For Paralympic athletes questions about dissatisfaction with body shape, may reflect directly to the disability and its challenges, such as the need to fit into a wheelchair or prosthesis, rather than being connected to an eating disorder. In individuals with visual impairment, body satisfaction appears to differ across age groups. A study on adolescents found that those with visual impairments reported higher body dissatisfaction, largely due to increased vulnerability to bullying and a greater reliance on external feedback about their appearance (93). In contrast, a study of women aged 20 to 35 years found that congenitally blind individuals experienced lower body dissatisfaction and more positive eating attitudes than their sighted peers, likely due to reduced exposure to visual media and cultural thin ideals throughout their development (94). Overall, Paralympic athletes may have higher or lower body image satisfaction directly due to their disability. Hence, the validity of the EDEQ questionnaire to assess the risk for eating disorders in Paralympic athletes is questionable. Due to the differences in body image in Paralympic athletes, the outcome of the EDE-Q can be skewed and probably a different scoring is necessary for Paralympic athletes. The questionnaire is not validated in a Paralympic cohort and should not be used as an indicator for LEA. The REDS CAT2 tool (50) also suggests assessing an eating disorder by a psychiatrist or psychologist. Although this is less accessible compared to the EDE-Q, it is likely to be more accurate and there is no reason to assume this is

unfit for the indication of the risk of LEA. The REDS CAT2 tool would, therefore, represent the preferred method for the assessment of an eating disorder in the Paralympic cohort.

Growth

Impaired growth is a primary indicator of LEA in adolescent athletes, and is defined as a deviation from a pediatric or adolescent athlete's previous growth trajectory (height and/or weight) (50). However, it is important to notice that several disabilities have growth defects inherent to the disability. Children with CP grow less well than their age related peers (95). This can in part be contributed to undernutrition but also to endocrine and neurological factors (62). 30 to 40% of children with CP experience feeding difficulties, leading to inadequate energy intake and inherently growth failure. However, also damage to the hypothalamus caused by CP, can lead to a modulated energy homeostasis and satiety (62). It is not clear if these feeding difficulties and damage to the hypothalamus are also present in adolescent athletes with CP. For athletes with short stature, impaired growth is inherent to their disability and not linked to LEA. Furthermore, it is not always possible to measure the stretch stature of a Paralympic athlete, due to inability to stand up straight. For research purposes we measured the length of those athletes in a supine position from the bottom of the heel to the top of the head. However, this can induce a bias in the measurement with the values not being applicable to compare to standard growth trajectories.

Secondary indicators

(LDL) Cholesterol

High total cholesterol and LDL cholesterol are secondary indicators for the risk of REDs. Increases in LDL are found in individuals with anorexia nervosa (96). The hypothesized reason for the high levels of LDL cholesterol is a change in hormone levels during starvation. T3, which is low during LEA, aids in the breakdown of cholesterol, which (in part) explains the high cholesterol levels during LEA. Additionally, low estrogen levels are also correlated with high LDL cholesterol levels. According to a meta-analysis, LDL levels are similar between individuals with SCI and individuals without a disability (97). For individuals with CP there is some evidence for high(er) levels of LDL (98). However, since LDL levels are also high in inactive individuals, it is not clear how the high LDL levels in individuals with CP relate to their PAL (98). For individuals with achondroplasia, LDL levels are commonly lower compared to controls

with a similar BMI and age (99). In conclusion, LDL cholesterol levels are likely not influenced by the disability itself and could, therefore, be used as an indicator for the risk of REDs. Caution is warranted when interpreting LDL levels of individuals with achondroplasia, because they have naturally low LDL cholesterol levels.

Depression and anxiety

A Secondary indicator for LEA is clinically diagnosed depression and/or anxiety (50). However, within the SCI and SB population depression is more prevalent compared to the general population (100, 101). Similarly, individuals with CP are at increased risk for depression and anxiety, but only when no intellectual disability is present (102). Also among individuals with a limb amputation the prevalence of depression is high. However, one of the main factors associated with greater depression symptomatology is activity restriction (103), which may not apply to the Paralympic population. Additionally, the visually impaired are also at a higher risk for depression (104). For people with skeletal dysplasia, such as achondroplasia, self-reported depression had a high prevalence of 34% (105). However, among physically active individuals with achondroplasia the quality of life and psychological well-being outcomes were higher compared to less active individuals, suggesting that the risk for depression in Paralympic athletes with achondroplasia is limited (106). Collectively, depression and anxiety seem more common among individuals with disabilities, and can be related to the disability rather than LEA.

Can REDs indicators be used for Paralympic athletes?

The use of the CAT2 REDs tool is an improvement in assessing the risk of REDs compared the calculation (Equation 7.3) with cut-off values. By incorporating multiple indicators, the CAT2 tool offers a more holistic approach. However, the diagnosis of REDs remains a 'diagnosis of exclusion' (50), as in that it can only be confirmed after ruling out alternative causes for the observed physiological or performance impairments. This makes the diagnosis of REDs in Paralympic athletes particularly challenging, due to many indicators for REDs being present due to the physiological, metabolic, and physical effects of different disabilities. Table 7.4 provides an overview of how different disabilities and wheelchair use can affect these indicators. When practitioners suspect a high risk of LEA and/or REDs in a Paralympic athlete, they must carefully consider how the disability may influence specific indicators. Some indicators should not be used at all with specific disabilities, because the disability may directly affect the indicator. As a result, a full application of the standard

IOC REDs CAT2 scoring system (Table 7.3) is not generally applicable. A more individualized approach is recommended, selecting indicators that are not affected by the individual's disability, or taking the disability into account when interpreting the indicators. Consequently, the classification of REDs risk as shown in Table 7.3, should be interpreted with caution and adapted to the possibilities within each individual.

Table 7.4. The severe primary, primary, and secondary indicators for the assessment of the risk for REDs and the applicability of the indicators for various disabilities.

Classification	Indicator	Influence of disability
Severe primary	Primary amenorrhea	SCD: no contraindications
		CP: late menarche possible
		LD: no contraindications
		VI: no contraindications
		SS: late menarche possible
	Prolonged secondary amenorrhea	SCD: no contraindications (after 5 months past the injury and no hormonal contraception)
		CP: earlier menopause possible
		LD: no contraindications (if no hormonal contraception)
		VI: no contraindications (if no hormonal contraception)
		SS: longer menstrual cycles possible
	Clinically low free or total testosterone	SCD: low testosterone common
		CP: hypogonadism possible
		LD: no contraindications
		VI: no contraindications
		SS: not clear
Primary	Secondary amenorrhea	See: Prolonged secondary amenorrhea
	Sub-clinically low or free testosterone	See: Clinically low free or total testosterone
	(Sub-)clinically low total or free T3	SCD: no contraindications
		CP: no contraindications
		LD: no contraindications
		VI: no contraindications

Table 7.4. The severe primary, primary, and secondary indicators for the assessment of the risk for REDs and the applicability of the indicators for various disabilities. (*continued*)

Classification	Indicator	Influence of disability
		SS: no contraindications except for cases with non-GF
	History of ≥1 high-risk or ≥2 low-risk BSI	WU: don't use or use other high and low risk places
		AM: no contraindications if loading patterns are normal
	Low BMD Z-score or decrease in BMD Z-score	WU: BMD is low at hip, possibly use other sites
		AM: no contraindications if loading patterns are normal
	Deviation from previous growth trajectory	SS: Growth deviation is part of the disability.
		Other: be careful with measurement technique and trajectories
	Elevated EDE-Q score and/or clinical ED diagnosis	EDE-Q: don't use, body image related
		Clinically diagnosed ED: no contraindications
Secondary	Oligomenorrhea	See: Prolonged secondary amenorrhea
	History of 1 low-risk BSI or <6 months of absence from training due to BSI	See: History of ≥1 high-risk or ≥2 low-risk BSI
	Elevated total or LDL cholesterol	SCD: no contraindications
		CP: no contraindications
		LD: no contraindications
		VI: no contraindications
		SS: caution, LDL levels are naturally low
	Clinically diagnosed depression or anxiety	High risk for all disabilities

Green = use the indicator; yellow = use the indicator with caution; red = don't use the indicator. SCD = spinal cord disorder; CP = cerebral palsy; LD = limb deficiency; VI = visual impairment; SS = short stature; T3 = triiodothyronine; GF = growth factor; BSI = bone stress injury; WU = wheelchair user; AM = ambulatory individuals; BMD = bone mineral density; EDE-Q = eating disorder examination questionnaire; ED = eating disorder.

CONCLUSION AND FUTURE DIRECTIONS

The aim of this thesis was to improve the nutritional counseling of Paralympic athletes by investigating their nutritional needs. Historically, nutritional guidelines for Paralympic athletes have been largely extrapolated from those developed for athletes without disabilities, despite significant differences in body composition, metabolism, and energy expenditure. A crucial element in creating athlete specific nutritional guidelines is an accurate assessment of TDEE. To close this knowledge gap, this thesis introduced new prediction equations for both TDEE and RMR specific to Paralympic athletes. However, estimating PAEE, a large part of TDEE, remains partly subjective and prone to error when relying on (for example) PAL values. Future research should optimize the estimation of PAEE of Paralympic athletes, possibly through the application of wearable technologies. These technologies are promising but require validation and adaptation to be used for the diverse impairments of Paralympic athletes. Beyond energy estimations, effective nutritional counseling depends on the correct implementation. Future research should explore practical barriers to adherence, such as gastrointestinal discomfort, incontinence, or fear of not fitting in a wheelchair, factors that may be limiting food and fluid intake. Qualitative research is needed to better understand these barriers and develop supportive strategies. Furthermore, Chapter 5 revealed a high prevalence of low BMD, especially at the hip in wheelchair users, increasing fracture risk. Intervention studies should investigate training strategies to counteract this issue. One potential approach is to incorporate exercises that involve rotational movements of the hip, where feasible, as similar movements in the lumbar spine have been associated with increased BMD. Finally, Chapter 6 uncovered a potential risk of nocturnal hypoglycemia in athletes with SCI. Since hypoglycemia in the night can impair recovery and even pose a health risk, larger studies are needed to confirm this finding and develop preventive strategies. In summary, this thesis lays the groundwork for better nutritional counseling of Paralympic athletes. The toolbox for practitioners working with these athletes has been extended with practical tools, such as new prediction equations. Additionally, this thesis provides a solid basis for future research, to further optimize both the assessment of energy needs and the application and implementation of tailored nutrition strategies in Paralympic athletes, ultimately supporting evidence based, individualized sport nutrition practice.

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Addendum

Summary
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SUMMARY

Para-sports is rapidly growing, highlighting the increasing need for proficient support of the athletes. Nutritional intake plays a critical role in both performance and health of an athlete. Effective nutritional counseling relies on an accurate assessment of the energy requirements of an athlete. While evidence-based nutritional guidelines exist for able-bodied athletes, similar frameworks for Para athletes remain limited. Yet, Para-athletes often have unique nutritional needs due to differences in body composition, energy expenditure during both exercise and daily life activities, and the nature and level of impairments. These differences necessitate research to assess total energy expenditure, nutritional intake, and body composition of Paralympic athletes to form the foundation for nutritional counseling of Paralympic athletes.

Accurate assessment of energy expenditure is essential for providing effective nutritional counseling. **Chapter 2** describes the total daily energy expenditure (TDEE) of Paralympic athletes across various disabilities and sport disciplines, measured with the golden standard, doubly labeled water method. The findings revealed that TDEE was generally moderate to high, although there was considerable variation between sports and individuals. This variation was largely explained by differences in fat free mass (FFM) and exercise duration. Additionally, the presence of spinal cord disorder (SCD), such as spinal cord injury or spina bifida, was associated with a lower energy expenditure. Given that direct measurements of TDEE are not always feasible in practice, novel prediction equations were developed to estimate TDEE in this population. Regarding dietary intake, most athletes met or exceeded protein recommendations, while carbohydrate intake was often low, indicating potential for improvement in fueling strategies.

In practice, the prediction of TDEE relies on an accurate estimation of the resting metabolic rate (RMR). In athletes without a disability, the RMR is primarily influenced by an athlete's FFM. However, Para-athletes often have an altered body composition compared to able-bodied athletes, affecting the RMR. In **Chapter 3**, RMR was measured in a large cohort of Paralympic athletes, alongside assessments of body composition and blood analysis. The results identified FFM, triiodothyronine concentrations, and the presence of SCD as the strongest predictors, collectively explaining 71% of the variance in RMR. Based on these results a novel prediction equation was developed, and preexisting prediction equa-

tions were evaluated against measured RMR values. The novel prediction equations derived from this study, along with the pre-existing equations of Chun *et al.* and Nightingale & Gorgey, showed strong agreements with measured values and are now recommended for estimating RMR in Paralympic athletes.

The FFM was the key determinant of both RMR and TDEE in our work, and was assessed using dual energy x-ray absorptiometry (DXA). While DXA provides accurate measurements, it is not always accessible in daily practice, where skinfold measurements are more commonly used. However, the validity and feasibility of using skinfold measurements to assess the FFM in Paralympic athletes remains uncertain. Therefore, in **Chapter 4** we compared body composition assessments using DXA and skinfold measurements in this population. The results demonstrated high feasibility of DXA scans in Paralympic athletes, whereas standard 8-site skinfold measurements proved more challenging to perform, due to deformed or missing limbs. However, when skinfold measurements were translated into a fat percentage they showed strong correlations with the fat percentage measured by DXA. Though the translation from skinfolds to fat percentages is discouraged, it is recommended to use skinfold measurements to track changes in body composition in the individual athlete over time.

Bone mineral density (BMD) is another important component of body composition and is influenced by both energy availability and mechanical loading. While insufficient energy intake can lead to reduced BMD, mechanical loading typically promotes BMD. However, in Paralympic athletes, loading patterns differ significantly from those of able-bodied athletes due to differences in ambulation and daily activities. In particular, wheelchair use reduces loading on the lower body, potentially affecting bone health. **Chapter 5** explored the prevalence of low BMD in Paralympic athletes and assessed potential predictors of BMD. The findings revealed a high prevalence of low BMD in the hip region, whereas lumbar spine BMD was less frequently affected. Key factors associated with low BMD included wheelchair dependence, low body mass, and participation in non-weight-bearing sports such as Para-cycling.

An emerging tool to aid with nutritional counseling is the continuous glucose monitor (CGM). This method offers real-time insights into glucose dynamics that can inform personalized fueling strategies, which is particularly useful in endurance sports like Para cycling. However, glucose

profiles of Para cyclists have not been characterized yet and differences in glucose regulation may exist in athletes with SCD. **Chapter 6** explores the glucose patterns of Para cyclists using CGM. Results showed that athletes remained within the euglycemic range throughout most of the day(s). Mild nocturnal hypoglycemia (<3.9 mmol/L) was occasionally observed, while severe hypoglycemia (<2.9 mmol/L) occurred almost exclusively in athletes with SCD. The validity of CGM readings was evaluated against capillary blood glucose measurements. Accuracy was acceptable at rest but declined during exercise. This effect was particularly evident in hand cyclists compared to cyclists, presumably because the sensor, which was placed on the upper arm for everyone, was located closer to the active muscle mass in hand cycling.

In summary, this thesis examined multiple aspects of the nutritional requirements of Paralympic athletes, including energy intake, TDEE, RMR, body composition, BMD, and glucose regulation. In **Chapter 7**, the results of this thesis are placed in a broader perspective. More specifically, practical guidance is provided for estimating the energy requirements of Paralympic athletes in an applied setting. Additionally, recommendations are offered for identifying and addressing low energy availability, supporting practitioners in delivering tailored, evidence-based nutritional care for this diverse and unique athletic population. The chapter is finalized by providing future directions to further optimize measurements or estimations of physical activity energy expenditure and tailoring nutritional strategies to Paralympic athletes, ultimately supporting more evidence based, individualized sport nutrition counseling.

SAMENVATTING

De Parasport groeit in een hoog tempo, waardoor de behoefte aan professionele begeleiding voor deze atleten toeneemt. Voeding speelt hierbij een cruciale rol voor zowel de sportprestaties als de gezondheid van de atleten. Om effectieve voedingsbegeleiding te bieden is een nauwkeurige schatting van de energiebehoefte essentieel. Voor atleten zonder beperking bestaan er wetenschappelijk onderbouwde voedingsrichtlijnen, maar voor Paralympische atleten zijn deze niet of nauwelijks beschikbaar. Dit terwijl Paralympische atleten vaak unieke voedingsbehoeften hebben, door verschillen in lichaamssamenstelling, energiegebruik tijdens sport en in het dagelijks leven, en de aard van hun beperking. Deze verschillen onderstrepen het belang van wetenschappelijk onderzoek naar het energiegebruik, voedingsinname en lichaamssamenstelling van Paralympische atleten, als basis voor passende voedingsadviezen.

Een nauwkeurige bepaling van het energiegebruik is essentieel om effectieve voedingsbegeleiding te kunnen bieden. In **Hoofdstuk 2** werd het totale dagelijkse energiegebruik van Paralympische atleten met verschillende beperkingen en sporten beschreven, gemeten aan de hand van de gouden standaard methode, dubbel gelabeld water. De resultaten toonden aan dat het totale dagelijkse energiegebruik varieerde van gemiddeld tot hoog, met aanzienlijke verschillen tussen sporten en individuen. Deze variatie kon grotendeels worden verklaard door verschillen in vetvrije massa en trainingsduur. Daarnaast bleek dat een aandoening aan het ruggenmerg, zoals een dwarslaesie of spina bifida, geassocieerd was met een lager energiegebruik. Aangezien directe metingen van het totale dagelijkse energiegebruik in de praktijk vaak niet mogelijk zijn, zijn nieuwe voorspellingsformules ontwikkeld om het totale dagelijkse energiegebruik van Paralympische atleten te kunnen schatten. Wat betreft de voedingsinname kregen de meeste atleten voldoende of zelfs teveel eiwitten binnen, terwijl de koolhydraat inname relatief laag was. Dit impliceert dat er ruimte is voor verbeteringen van de macronutriënten verdeling.

In de praktijk is een nauwkeurige schatting van het rustmetabolisme essentieel voor het voorspellen van het totale dagelijkse energiegebruik. Bij atleten zonder beperking wordt het rustmetabolisme voornamelijk beïnvloed door de vetvrije massa. Paralympische atleten hebben echter vaak een afwijkende lichaamssamenstelling in vergelijking met atleten zonder beperking, wat invloed heeft op hun rustmetabolisme. In **Hoofdstuk 3** is het rustmetabolisme gemeten bij een grote groep Paralympische

atleten, waarbij gelijktijdig de lichaamssamenstelling werd bepaald en bloedanalyses zijn uitgevoerd. Uit de resultaten kwam naar voren dat vetvrije massa, tri-joodthyronine concentraties, en de aanwezigheid van een aandoening aan het ruggenmerg de sterkste voorspellers waren en samen 71% van de variatie in rustmetabolisme konden verklaren. Op basis van de resultaten zijn nieuwe voorspellingsformules ontwikkeld en zijn bestaande voorspellingsformules geëvalueerd ten opzichte van de gemeten waarden van het rustmetabolisme. De nieuw ontwikkelde voorspellingsformules, evenals de al bestaande formules van Chun *et al.* en Nightingale & Gorgey, kwamen het beste overeen met de gemeten waarden en worden daarom aanbevolen voor het schatten van het rustmetabolisme bij Paralympische atleten.

De vetvrije massa, gemeten aan de hand van dual-energy X-ray absorptiometry (DXA), bleek in onze studies de belangrijkste determinant van zowel rustmetabolisme als totaal dagelijks energiegebruik. Hoewel DXA een nauwkeurige methode is om vetvrije massa vast te stellen, is deze in de praktijk niet altijd beschikbaar. In de praktijk wordt daarom vaker gebruik gemaakt van huidplooimetingen. De validiteit en praktische haalbaarheid van huidplooimetingen voor het bepalen van de vetvrije massa van Paralympische atleten is echter onzeker. Daarom hebben we in **Hoofdstuk 4** de lichaamssamenstelling gemeten met behulp van DXA scans en vergeleken met resultaten op basis van huidplooimetingen. De resultaten lieten zien dat het uitvoeren van DXA scans over het algemeen goed haalbaar was bij Paralympische atleten. De gestandaardiseerde methode met acht huidplooien bleek in een aantal gevallen moeilijker of onuitvoerbaar, vooral vanwege vergroeide of ontbrekende ledematen. Wanneer de huidplooidikte vertaald werd naar een vetpercentage, bleek er echter wel een sterke correlatie te zijn met het vetpercentage gemeten met DXA. Daarom wordt een algemene vertaling naar vetpercentage afgeraden, maar wordt er wel aanbevolen om de som van het aantal beschikbare huidplooien te gebruiken om lichaamssamenstelling over tijd te monitoren.

Botmineraaldichtheid is een ander belangrijk aspect van de lichaamssamenstelling en wordt beïnvloed door zowel energiebeschikbaarheid als mechanische belasting. Waar onvoldoende energie-inname kan leiden tot een verlaagde botmineraaldichtheid, heeft mechanische belasting juist een stimulerend effect. Bij Paralympische atleten wijken belastingspatronen tijdens voortbeweging en dagelijkse activiteiten sterk af van die van atleten zonder beperking. Met name rolstoelgebruik vermindert de belas-

ting van het onderlichaam, wat potentieel negatieve gevolgen heeft voor de botmineraaldichtheid. In **Hoofdstuk 5** is de prevalentie van een lage botmineraaldichtheid onderzocht, evenals potentiële voorspellers ervan. De resultaten toonden een hoge prevalentie van lage botmineraaldichtheid in de heupregio, terwijl de lumbale wervelkolom minder vaak was aangedaan. De belangrijkste factoren die botmineraaldichtheid negatief leken te beïnvloeden waren rolstoelgebruik, een laag lichaamsgewicht en deelname aan niet-gewicht dragende sporten, zoals Parawielrennen.

Een opkomend hulpmiddel voor voedingsbegeleiding is de continue glucosemonitor (CGM). Deze technologie biedt realtime inzicht in de dynamiek van bloedglucose concentraties en kan daarmee bijdragen aan gepersonaliseerde voedingsstrategieën, met name voor duuratleten zoals Parawielrenners. Tot nu toe zijn de glucoseprofielen van Parawielrenners echter nauwelijks onderzocht. **Hoofdstuk 6** onderzocht de glucosepatronen van Parawielrenners met behulp van continue glucosemonitors. De resultaten laten zien dat de meeste atleten over het algemeen binnen de euglykemische waarden blijven. Lichte hypoglykemie (<3,9 mml/L) werd sporadisch gemeten, terwijl ernstige hypoglykemie (<2,9 mmol/L) vrijwel uitsluitend voorkwam bij atleten met aandoeningen aan het ruggenmerg. De validiteit van de continue glucosemonitormetingen werd geëvalueerd door een vergelijking met capillaire bloedglucosemetingen. Hoewel de continue glucosemonitor een acceptabele nauwkeurigheid had in rust, nam de meetnauwkeurigheid af tijdens inspanning. Dit effect was vooral duidelijk bij handbikers in vergelijking met fietsers, vermoedelijk doordat de sensor, die bij iedereen op de bovenarm was geplaatst, bij handbikers dichterbij de actieve spiermassa zat.

Samenvattend onderzocht deze thesis verschillende aspecten van de voedingsbegeleiding van Paralympische atleten, waaronder energie-inname, totaal dagelijks energiegebruik, rustmetabolisme, lichaamssamenstelling, botdichtheid en glucoseregulatie. In **Hoofdstuk 7** worden de bevindingen van deze thesis in een breder perspectief geplaatst. Dit hoofdstuk biedt praktische handvaten voor het schatten van de energiebehoefte van Paralympische atleten. Daarnaast worden aanbevelingen gedaan voor het signaleren van een lage energie beschikbaarheid in deze populatie. Het hoofdstuk wordt afgesloten met suggesties voor toekomstig onderzoek gericht op het nauwkeuriger schatten van energiegebruik tijdens fysieke activiteit en het ontwikkelen van gepersonaliseerde voedingsstrategieën. Hiermee vormt deze thesis de basis voor een meer wetenschappelijk onderbouwde, individuele sportvoedingsaanpak voor Paralympische atleten.

IMPACT

The aim of this thesis was to investigate the nutritional requirements of Paralympic athletes by enhancing our understanding of the energy expenditure and body composition across a wide range of disabilities and sport categories. While proper nutrition is essential for both performance and health, current guidelines for Paralympic athletes are largely based on research in able-bodied populations, despite clear physical and or physiological differences. Therefore, gaining deeper insight into the unique nutritional demands of Paralympic athletes is crucial. This research demonstrated for the first time, through the gold standard doubly labeled water (DLW) method, that total daily energy expenditure (TDEE) among Paralympic athletes varies widely, influenced by fat free mass (FFM), the type of disability, and the exercise duration. We developed the first prediction equations for estimating the TDEE and resting metabolic rate (RMR) specifically tailored to Paralympic athletes. Additionally, we showed that skinfold-based methods are a valid assessment method for tracking Paralympic athlete's body composition but should not be translated to a fat percentage. We also provided evidence that the prevalence of low bone mineral density (BMD) was high in the hip and femoral neck, especially among wheelchair dependent athletes, while BMD of the lumbar spine was relatively normal. Finally, we highlighted the need to adapt the existing method for assessing low energy availability, as it does not adequately account for disability related factors. The broader impact of this thesis in terms of scientific relevance, the target population and societal relevance, as well as the implications for translation into practice will be discussed below.

Scientific relevance

This research broadens our understanding of the factors influencing the nutritional needs of Paralympic athletes. By generating essential data from a largely understudied population, we have made substantial contributions to the field of sports nutrition. In particular, we provided new insights into the ongoing debate on whether the variation in RMR between individuals with and without a spinal cord disorder (SCD) can be solely explained by the reduction in FFM (1–4). Our findings demonstrate that individuals with SCD have a reduced RMR, even after adjusting for FFM, likely due to decreased sympathetic nervous system activity. We also strengthened the evidence supporting the importance of mechanical loading for BMD and suggested that torsional loading may be particularly effective in improving BMD. This insight could improve future interven-

tion strategies aiming to increase the BMD in populations who are at risk, by incorporating exercises that include torsional loading. Additionally, we evaluated the validity of the emerging continuous glucose monitoring (CGM) tools in this unique athletic population. Our findings showed differences in reliability between handbikers and cyclists, likely due to the varying proximity of the sensor to active muscle tissue. This information is crucial for future research with CGM. All findings from this thesis have been disseminated through peer-reviewed publications, except for the article on body composition, which is under consideration. Additionally, the results have been presented at world-leading conferences such as the European College of Sport Science (ECSS) congress, the International Sport and Exercise Nutrition Conference (ISENC), the International Paralympic Committee (IPC) VISTA conference, and the European Sport Nutrition Society (ESNS) conference, ensuring the integration into the broader sport science and nutrition community.

Target groups and societal relevance

All studies in this thesis were conducted with elite level Paralympic athletes to assess their specific nutritional needs. Due to the inclusion of various disabilities, sports, ages, both sexes, and two countries of origin, the heterogeneity of the participants was high. While this diversity makes it more challenging to draw definitive conclusions, it does enhance the generalizability of the findings to the broader Paralympic population. The aim of this research was to aid professionals working with Paralympic athletes in giving scientifically based nutritional counseling. They can use these insights to provide more effective and individualized dietary guidance aimed at optimizing health and performance. This in turn aids the Paralympic athletes, who receive better counseling. Moreover, the findings are relevant to a wider audience, including athletes with disabilities who are active in recreational sport, but may not compete at the Paralympic level. This thesis lays a strong foundation for future research focused on the nutritional needs of non-elite Para athletes. Beyond the athletic and scientific communities, the implications of this work extend to sports organizations, policymakers, and the food industry. These stakeholders can use the findings from this thesis to inform the development of tailored nutrition products and services that address the unique energy demands and dietary needs of individuals with disabilities who engage in physical activity.

Because the target audience may not read academic papers or attend international conferences, we also shared the knowledge through more accessible and practice oriented pathways. We presented our results at national events such as the Nederlands Vlaams Dwarslaesie Genootschap (NVDG) congress, the Vereniging van Bewegingswetenschappen Nederland congress (VvBN), and the Dag van het SportOnderzoek (DSO). These events are commonly attended by practitioners to stay up to date on scientific developments. Moreover, the results were presented during masterclasses specifically organized for sports nutritionists affiliated with the Vereniging Sportdiëtiek Nederland (VSN), as well as for the sports physicians and physiotherapists supporting the Paralympic division of TeamNL. In this way the knowledge was disseminated in a more practical manner directly to the professionals working with the Paralympic athletes. Additionally, we created a clear and practical summary of our findings, which is published at Paralympicsciencesupport.nl, and can be used by coaches, dietitians, and other professionals. Finally, to broaden our reach, we shared our results via podcasts and social media.

Translating our findings into practice

The findings of the studies included in this thesis are highly practical. Individual results such as TDEE and RMR were shared with the athletes or their dieticians, allowing for immediate use in their personal dietary advise. This may have directly influenced the nutrition plans of the athletes who took part in the research. On a broader level, the methods developed to estimate energy needs, assess body composition, and monitor glucose levels in Paralympic athletes can help practitioners provide better, more personalized nutritional counseling. Moreover, knowledge from our research is used in education for sport nutrition students to inform them on the unique nutritional requirements of these athletes. We already had positive responses from students and professionals in the field who work with our equations and use the knowledge in daily practice when working with Para athletes. Therefore, it is safe to say this thesis offers clear, science-based guidance that can be applied in practice to improve both the health and performance of Para athletes.

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