Towards a healthier lifestyle in wheelchair users

Hoevenaars, Dirk Pieter

2022

document version
Publisher's PDF, also known as Version of record

Towards a healthier lifestyle of wheelchair users:

the potential of mHealth and wearables

Dirk Hoevenaars

This PhD thesis was embedded within and supported by Amsterdam Movement Sciences research institute at the Department of Human Movement Sciences, Vrije Universiteit, Amsterdam, the Netherlands.

The research described in this thesis was supported by the Netherlands Organisation for Scientific Research (NWO), Regie orgaan SIA en FAPESP (629.004.011).

Amsterdam Movement Sciences conducts scientific research to optimize physical performance in health and disease based on a fundamental understanding of human movement in order to contribute to the fulfillment of a meaningful life.

Support for printing this thesis was kindly provided by Amsterdam Rehabilitation Research Center Reade, Coloplast, Korter Maar Krachtig, Fonds Gehandicaptensport, Sport Data Valley and Virtuagym.

Provided by thesis specialist Ridderprint, ridderprint.nl

Cover design Joost Oosterwijk

Layout design Jules Verkade, persoonlijkproefschrift.nl

Printed by Ridderprint

ISBN 978-94-6458-517-9

VRIJE UNIVERSITEIT

TOWARDS A HEALTHIER LIFESTYLE IN WHEELCHAIR USERS: THE POTENTIAL OF MHEALTH AND WEARABLES

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad Doctor of Philosophy
aan de Vrije Universiteit Amsterdam,
op gezag van de rector magnificus
prof.dr. J.J.G. Geurts,
in het openbaar te verdedigen
ten overstaan van de promotiecommissie
van de Faculteit der Gedrags- en Bewegingswetenschappen
op vrijdag 9 december 2022 om 13.45 uur
in een bijeenkomst van de universiteit,
De Boelelaan 1105

door

Dirk Pieter Hoevenaars

geboren te 's-Hertogenbosch

promotoren:	prof.dr. T.W.J. Janssen
	prof.dr.ir. W. Kraaij
copromotoren:	dr. S. de Groot
	dr. J.F.M. Holla
promotiecommissie:	prof.dr. M. Pijnappels
	prof.dr. J.H.P. Houdijk
	prof.dr. R. Dekker
	dr. H.J.G. van den Berg-Emons
	dr. M. Vos-van der Hulst

Table of Contents

Chapter 1

General introduction

Health and Lifestyle

Being in good health is by many one of the most important aspects of life. With good health, most people refer to the so-called positive health. This is a concept of the absence of illness, good daily functioning and quality of life influenced by contextual factors leading to physical, social and emotional well-being [1]. A person can actively influence this to a certain extent, i.e., by maintaining a healthy lifestyle to create the best circumstances to achieve and stay in good health [2,3]. Yet, a major part of the European society fails to do so and struggles to adopt and maintain healthy behavior, approximately only 1.3% to 9.2% of the people within European countries maintain a healthy lifestyle [4–6]. Unhealthy lifestyle leads to increased risk of a variety of diseases, increased mortality rate and reduced quality of life [4–7]. The amount of influence someone has on their lifestyle varies among people. External factors such as living environment and socioeconomic status are difficult to change, and interact with lifestyle and health [8–10]. Important and common behaviors associated with a healthy lifestyle that can be influenced are physical activity, diet, alcohol consumption, smoking and sleep quality [4,11–14]. Although healthy lifestyle is a broad and complex construct, for the ease of the remaining thesis, healthy lifestyle is referred to as the combination of healthy physical activity, dietary and sleep behavior.

Health and Lifestyle in Wheelchair users

Physical activity, diet, and sleep behavior are all determinants of behavior that can actively be changed and influenced by oneself to a certain extent. Although this already seems challenging enough for the common society, this is even more difficult for wheelchair users with a chronic disability [15–18]. Physical impairments, and subsequently becoming wheelchair dependent causes additional daily external physical, social and societal barriers. The likelihood of people with lower extremity mobility difficulties, i.e. wheelchair users, to develop obesity, is up to 2.5 times greater compared to those without [19]. This is mostly caused by an imbalance between energy intake and total daily energy expenditure as depicted in figure 1. Wheelchair users with a chronic disability show lower physical activity levels compared to the general population, reducing the activity energy expenditure [20]. Physiological changes due to their physical condition further reduce their total energy expenditure, e.g., due to a lower resting energy expenditure, which is commonly found in physically disabled people [21]. Wheelchair users with different chronic conditions show poorer diet quality choices compared to the general population, often defined by increased intake of fat and sugar and limited intake of fruit, whole grains and dairy [17,18,22]. This is often combined with sleep difficulties, which manifests itself as sleep disorders [23] and psychological distress [24] which again is related to obesity [14,25]. The accumulation of these factors all contribute to an unhealthy lifestyle resulting in poorer mental health [26], increased obesity rates and corresponding health risks such as cardiovascular disease, diabetes and multiple forms of cancer [3]. Therefore, physical activity, dietary behavior and sleep should be targeted simultaneously. These factors are all intertwined with each other and the onset of undesirable unhealthy behavior can aggravate other lifestyle-related factors, causing a vicious circle, which can be very challenging to interrupt and reverse.

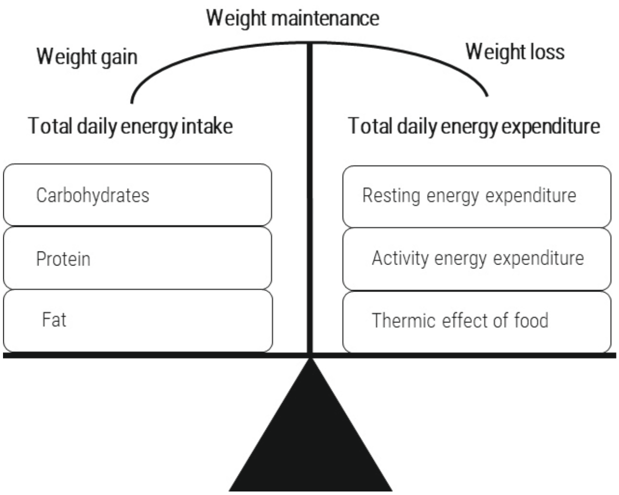


Figure 1. Energy balance between energy intake and energy expenditure and its involved components.

Physical activity in wheelchair users

As most people know, being physical active has many health benefits, such as a reduced risk of cancer, cardiorespiratory, musculoskeletal and metabolic health which directly improve physical fitness, but is also related to improved cognitive and mental health, quality of life and sleep [27,28]. Despite this knowledge, a large proportion world-wide fails to achieve a healthy physical activity level [7]. People with chronic disabilities show even lower physical activity levels, clearly depicted in Figure 2 [20]. People with chronic disabilities, especially those who are wheelchair bound, such as people with spinal cord injury (SCI) or lower-limb amputation, show low levels of physical activity and are depicted on the right side of the spectrum in figure 2. Being physically active and physically fit may be even more important for wheelchair users compared to the general population as it is more likely to influence their daily functioning [29] and is related to the experienced physical strain during daily life [30]. This makes physical activity promotion for wheelchair users even more crucial and necessary. The World Health Organization (WHO) developed scientifically grounded physical activity guidelines and has updated these regularly [27,28]. These guidelines provide information and guidance on the dose-response relationship between frequency, duration and intensity of physical activity and the corresponding health outcomes. For some wheelchair users with chronic disabilities, these guidelines may not be suitable due to physiological changes and altered responses to physical activity. A good example are individuals with SCI. Therefore, two SCI population specific exercise guidelines were developed to provide the best evidence-based recommendations [31,32]. However, it is unclear which proportion of the Dutch wheelchair users with SCI are meeting these SCI exercise guidelines. Knowing the proportion of Dutch wheelchair users with SCI meeting these SCI exercise guidelines would provide insight on the necessity of physical activity promotion. Together with the associated physical fitness and health benefits it would show the value of meeting these SCI exercise guidelines and the importance of sufficient physical activity. Therefore, the proportion of Dutch people with SCI meeting these guidelines together with the associated demographics and the physical fitness and health benefits were investigated and are presented in chapter 2.

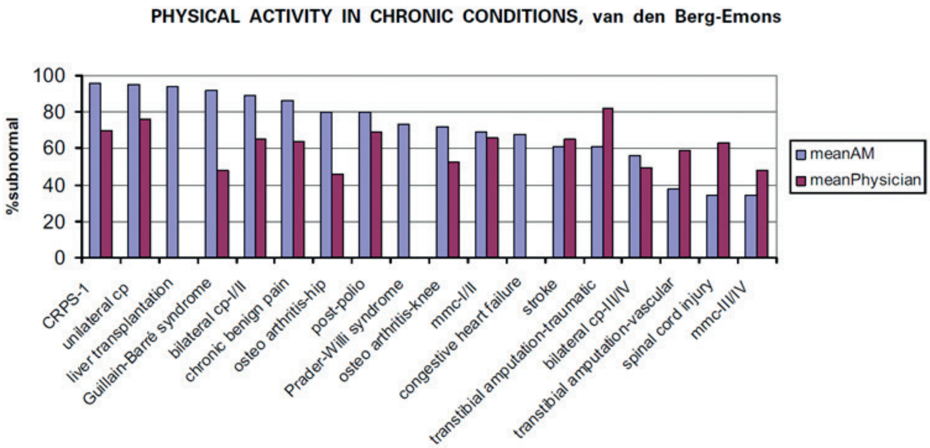


Figure 2. Relative time on physical activities in people with chronic disabilities determined by accelerometry and estimated by rehabilitation physicians compared to age-related abled-bodied counterparts. CRPS-1, complex regional pain syndrome type 1; Unilateral CP, unilateral cerebral palsy; Bilateral CP-I/II, bilateral cerebral palsy with gross motor functioning class I/II; MMC-I/II, myelomeningocele with Hoffer class I/II; Bilateral CP-III/IV, bilateral cerebral palsy with gross motor functioning class III/IV; MMC-III/IV, myelomeningocele with Hoffer class III/IV. Figure obtained from van den Berg-Emons et al. (2010) [20].

Dietary behavior in wheelchair users

Another important aspect of a healthy lifestyle is diet, which is considered a critical part of health according to the World Health Organization [33]. A healthy diet helps preventing many chronic diseases such as cardiovascular disease, different forms of cancer and diabetes [34]. Although a diverse and varied diet is also influenced by geographical location and culture, the foundation of a healthy diet remains similar. There is a strong relationship between diet and being overweight or obese, as the general cause for this is an imbalance between energy intake (diet) and energy expenditure [35,36]. Due to a reduced resting energy expenditure and activity energy expenditure in wheelchair users, the likelihood of a surplus of energy intake increases. People struggle to adapt their energy intake to their new reduced total daily energy expenditure in their chronic condition after discharge, often due to the lack of knowledge and awareness [17,18]. This disturbed energy balance eventually contributes to an increased prevalence of overweight and obesity and corresponding health risks in wheelchair users, which in response can negatively influence physical activity and sleep behavior and vice versa [37]. Despite this knowledge it appears difficult for wheelchair users to maintain a healthy diet and energy balance. Research showed that poor diet choices are common in people with lower-limb amputation or SCI [18,38] and a surplus of energy intake is often reported in people with SCI [17]. However, despite their surplus in energy intake compared to their energy expenditure, the risk remains for deficiencies in micronutrients intake such as vitamins and minerals due to their lower total intake [17]. This makes a balanced energy intake and expenditure combined with sufficient micronutrients extra challenging in wheelchair users with a chronic disability. Promoting a healthy diet is therefore crucial for wheelchair users. Providing a more accurate insight in their energy balance could support this.

Sleep quality in wheelchair users

Sleep is just like diet and physical activity an important lifestyle-related behavior and related to health and well-being [39,40]. Sleep has an effect on, among other things, immune function, learning, memory and emotional regulation [41,42]. Wheelchair users with chronic disabilities have reported poorer sleep quality [43], which is related to a decreased health-related quality of life [44] and increased risk of obesity [14]. Sleep is also related to both dietary and physical activity behavior. Previous research has shown that a reduced sleep duration leads to an increased appetite, resulting in an increased food intake [45,46], directly influencing dietary behavior and its corresponding daily energy balance. On top of an increased appetite, a reduced sleep duration is associated with increased fatigue and reduced physical activity [47], making sleep an important factor contributing to a healthy lifestyle.

Wearables

Wearable technology is often used in healthy lifestyle promotion as it can provide real time feedback as it is incorporated with self-tracking features on lifestyle behavior, including physical activity and sleep behavior. A wrist-worn activity tracker is currently the most popular wearable [48]. Common features that are provided, which are based on multiple variables, are an estimation of the users' physical activity level, energy expenditure, training intensity and sleep quality. The opportunity to know one's physical activity level is important, as it could give insight in whether the recommended physical activity levels are achieved. In addition, having a valid estimation of one's energy expenditure could support a weight transition, as weight management is largely dependent on the balance between energy intake and energy expenditure [36]. Common sensor technologies used to achieve these estimations are a 3-axis accelerometer, gyroscope and photoplethysmography (PPG). PPG determines heart rate based on blood volume changes and is used in many of the available features of a wearable, making it an important parameter. However, wearables are often not developed and designed for wheelchair users with chronic disabilities. Accuracy of the collected data could be influenced due to physiological changes by their disability. This might be in the situation of PPG-based heart rate registration in people with SCI. The autonomic nervous systems (ANS) is affected in people with SCI, which affects the balance between the parasympathetic and sympathetic system and, therefore, often the blood pressure regulation in the upper limbs [49]. This could directly influence the accuracy of wearables, as in most cases the heart rate is measured with the PPG technique at the wrist. The ANS is more affected in cervical lesions, as the imbalance between the parasympathetic and sympathetic increases with lesion level [50]. Therefore, the accuracy of heart rate measured by the PPG technique in people with SCI and its effect of lesions level was investigated and is presented in chapter 3.

mHealth

With increasing healthcare costs in Europe, including the Netherlands, it is suggested to redesign healthcare, with a priority to provide sustainable care and prevention in a cost-effective way [51,52]. To achieve and maintain a healthy lifestyle, many different technological developments are available in the field of health promotion to support this goal. These developments are expected to rapidly continue in the next decades [53]. The development of mobile health (mHealth) and wearable technology allows incorporation of advanced electronic and computer technologies to support the transition towards and maintaining a healthy lifestyle on an individual and group level [54]. Its ability for widespread availability, easy accessibility and reducing intervention time and costs making it, therefore, possibly a good solution to reduce healthcare costs [55,56]. A key benefit for the users of mHealth is that it can be accessed anytime and anywhere, hence removing potential barriers. This is especially valuable for wheelchair users, as they often encounter more physical and social barriers during daily life than for able-bodied persons, such as inaccessibility of public places [57,58]. The ability to self-manage their maintenance or transition towards a healthy lifestyle through tailored feedback can empower these individuals [59,60]. However, often both mHealth and wearables are not specifically designed or tested for wheelchair users with chronic disabilities. So, on top of their daily additional barriers and challenges, for this specific population fewer opportunities and less support are available in the form of mHealth and wearable technology to support a healthy lifestyle. To overcome this gap, the WHEELS lifestyle mHealth application was developed, focusing on physical activity, diet and sleep. An example of some of the functions of the WHEELS app are shown in figure 3. Previous research showed that the approach focusing on a combination of behaviors (i.e., physical activity, dietary and sleep behavior) is superior in improving health and weight management compared to interventions focusing on a single behavior, and is therefore, preferred [61,62]. The development and the usability and feasibility of the WHEELS app is described and investigated in a pilot study and presented in chapter 4.

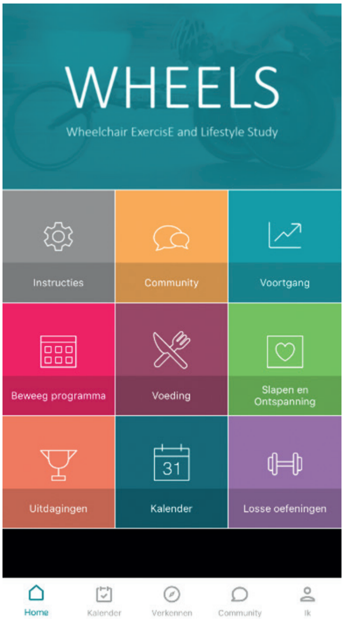


Figure 3. Home screen of the WHEELS lifestyle app.

mHealth and Wearables

The effectiveness of an mHealth lifestyle intervention is dependent on many factors, which can best be explained using the model of internet interventions shown in figure 4 [63]. This model was adjusted to an mHealth product and depicts how mHealth together with the support relates to potential behavior change and how personal and environmental factors influence mHealth use and thus behavior change results of the intervention. Support can be blended, involving face-to-face guidance, or remote-guided, involving distanced guidance through in-app or phone communication for example. The intervention is considered as stand-alone when no support is provided and solely the application is used as intervention. The mHealth product involves multiple aspects such as: appearance, behavioral prescriptions, burdens, content, delivery, message, participation and assessment, all affecting the exposure of behavior change techniques, usability and user experience and, therefore, effectiveness (figure 4). This model can be applied to all the intervention goals, i.e., healthy physical activity, dietary and sleep behavior, with each goal having their own mHealth components supporting this. The integration of an activity tracker into mHealth allows the usages of additional behavior change techniques, or the ability to provide a similar behavior change techniques present in mHealth with a different mode of delivery. This increases the exposure to behavior change techniques and thus supporting the intervention goals [64]. Important behavior techniques targeting key determinants of lifestyle behavior, such as self-monitoring, feedback on behavior and goal setting are all present and optional in activity trackers [65]. These techniques are presented in a convenient way, which is valued by users and could support a transition towards healthier behavior [66]. If these functionalities are well integrated into mHealth and used optimally, the behavior change effects can be significantly larger [67]. Therefore, the combination of wearable use and mHealth can complement each other and strengthen the delivery of behavior change techniques. Wearable use reduces the burden of the user by automatically measure lifestyle-related outcomes such as physical activity and sleep quality, provide additional content and information and thus improve the mHealth experience influencing the effectiveness. To evaluate whether the WHEELS app combined with wearable integration supports behavior change, an intervention study was conducted. In chapter 5 results are presented of changes in lifestyle and health in wheelchair users with a chronic disability after a 12-week intervention period in combination with an activity tracker.

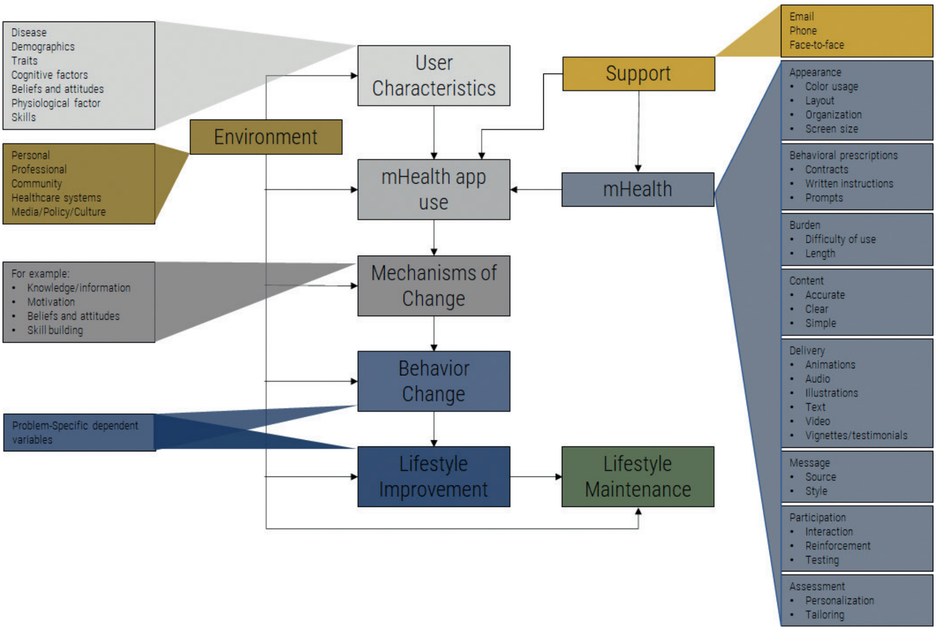


Figure 4. A behavior change model for internet intervention [63].

Outline of the thesis

The main research question of this thesis can be stated as: can wheelchair users improve their lifestyle and health using a combination of standard wearable sensors and a customised mHealth platform?

To answer this question, this thesis aimed to gain insight in the lifestyle of wheelchair users, provide an evidence-based mHealth application, combined with wearable technology, and evaluate lifestyle changes during a 12-week intervention in wheelchair users with a chronic lower-limb disability.

Chapter 2 describes a study in which it was estimated what proportion of the Dutch wheelchair users with chronic SCI were meeting two different SCI exercise guidelines and which demographic and lesion characteristics are associated in meeting these guidelines. In addition, it was investigated how meeting these guidelines is associated with better physical fitness and health.

Chapter 3 evaluates whether a Fitbit Charge 2 can accurately record heart rate in wheelchair users with chronic SCI. The effect of lesion level on accuracy was investigated by comparing accuracy between different lesion groups during different activities. Furthermore, the effect of activity intensity during wheelchair activities compared to rest was evaluated.

The developmental process of the WHEELS mHealth app and results of a usability and feasibility study are presented in **chapter 4**. In this chapter, the development, using the intervention mapping framework, towards an evidence-based mHealth app for wheelchair users is described. In follow-up, a pilot study was conducted to evaluate the usability and feasibility of the mHealth app and explore the effectiveness.

Chapter 5 evaluates the lifestyle changes of wheelchair users with a chronic lower-limb disability after 12 week using the WHEELS mHealth app. Lifestyle-related outcomes physical activity, diet, sleep behavior and body composition were measured, together with secondary lifestyle and health-related outcomes. In addition, it was explored whether a change in stage of change was related to actual behavior change.

The main findings and conclusions of all the chapters are summarized and discussed in the general discussion in **Chapter 6.**

References

1. Mezzich JE. Positive Health: Conceptual Place, Dimensions and Implications. Psychopathology. 2005;38:177–9.
2. World Health Organization. Global Action Plan for the Prevention and Control of Noncommunicable Diseases 2013-2020. Geneva; 2013.
3. World Health Organization. Global Health Risks: mortality and burden of disease attributable to selected major risks. Geneva; 2009.
4. Marques A, Peralta M, Martin J, Loureiro V, Almanzar PC, de Matos MG. Few European Adults are Living a Healthy Lifestyle. Am J Heal Promot. 2018;33(3):391–8.
5. Springmann M, Mozaffarian D, Rosenzweig C, Micha R. What we eat matters: Health and environmental impacts of diets worldwide. In: 2021 Global Nutrition Report, the state of global nutrition. 2021. p. 34–49.
6. Marques A, Loureiro N, Avelar-rosa B, Naia A, de Matos MG. Adolescents ' healthy lifestyle. J Pediatr. 2020;96(2):217–24. [doi:10.1016/j.jped.2018.09.002]
7. Guthold R, Stevens GA, Riley LM, Bull FC. Worldwide trends in insufficient physical activity from 2001 to 2016: a pooled analysis of 358 population-based surveys with 1.9 million participants. 2018;6(10):1077–86. [doi:10.1016/S2214-109X(18)30357-7]
8. Centraal Bureau voor de Statistiek. Gezonde levensverwachting; onderwijsniveau. 2017 [cited 2022 Feb 21]. URL:http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=83780NED&LA=NL
9. Marmot M. Social determinants of health inequalities. Lancet. 2005;365(9464):1099–104.
10. Dahlgren G, Whitehead M. Policies and strategies to promote social equity in health. Stockholm; 1991.
11. World Health Organization. Prevention and Control of Noncommunicable Diseases in the European Region: A Progress Report. Copenhagen; 2014.
12. Brownson RC, Remington PL, Wegner M V. Chronic Disease Epidemiology and Control. 4th ed. Washington, DC: American Public Health Association; 2016.
13. Rayner M, Wickramasinghe K, Williams J, McColl K, Mendis S. An Introduction to Prevention of Non-Communicable Diseases. Oxford, England: Oxford University Press; 2017.
14. Wu Y, Zhai L, Zhang D. Sleep duration and obesity among adults: A meta-analysis of prospective studies. Sleep Med. 2014;15(12):1456–62. [doi:10.1016/j.sleep.2014.07.018]
15. van den Berg-Emons RJ, Bussmann JB, Haisma JA, Sluis TA, van der Woude LH, Bergen MP, et al. A Prospective study on physical activity levels after spinal cord injury during inpatient rehabilitation and the year after discharge. Arch Phys Med Rehabil. 2008;89(11):2094–101.
16. Desveaux L, Goldstein RS, Mathur S, Hassan A, Devlin M, Pauley T, et al. Physical activity in adults with diabetes following prosthetic rehabilitation. Can J Diabetes. 2016;40(4):336–41. [doi: 10.1016/j.jcjd.2016.02.003]
17. Farkas GJ, Pitot MA, Berg AS, Gater DR. Nutritional status in chronic spinal cord injury: a systematic review and meta-analysis. Spinal Cord. 2019;57(1):3–17.
18. Westerkamp EA, Strike SC, Patterson M. Dietary intakes and prevalence of overweight/obesity in male non-dysvascular lower limb amputees. Prosthet Orthot Int. 2019;43(3):284–92.
19. Weil E, Wachterman M, Mccarthy EP, Davis RB, Day BO, Iezzoni LI, et al. Obesity Among Adults With Disabling Conditions. J Am Med Assoc. 2002;288(10):1265–8.

20. Van Den Berg-Emons RJ, Bussmann JB, Stam HJ. Accelerometry-based activity spectrum in persons with chronic physical conditions. Arch Phys Med Rehabil. 2010;91(12):1856–61. [doi:10.1016/j.apmr.2010.08.018]

21. Da Silva Gomes AI, Dos Santos Vigário P, Mainenti MRM, De Figueiredo Ferreira M, Ribeiro BG, De Abreu Soares E. Basal and resting metabolic rates of physically disabled adult subjects: A systematic review of controlled cross-sectional studies. Ann Nutr Metab. 2014;65(4):243–52.

22. Walters JL, Buchholz a C, Martin Ginis K a. Evidence of dietary inadequacy in adults with chronic spinal cord injury. Spinal cord Off J Int Med Soc Paraplegia. 2009;47(4):318–22.

23. Giannoccaro MP, Moghadam KK, Pizza F, Boriani S, Maraldi NM, Avoni P, et al. Sleep disorders in patients with spinal cord injury. Sleep Med Rev. 2013;17(6):399–409. [doi:10.1016/j.smrv.2012.12.005]

24. Post MWM, Van Leeuwen CMC. Psychosocial issues in spinal cord injury: A review. Spinal Cord. 2012;50(5):382–9. [doi:10.1038/sc.2011.182]

25. Marshall NS, Glozier N, Grunstein RR. Is sleep duration related to obesity? A critical review of the epidemiological evidence. Sleep Med Rev. 2008;12(4):289–98.

26. Cabello M, Miret M, Caballero FF, Chatterji S, Naidoo N, Kowai P, et al. The role of unhealthy lifestyles in the incidence and persistence of depression: a longitudinal general population study in four emerging countries. Glob Heal. 2017;13(18).

27. World Health Organization. Global recommendations on physical activity for health. Geneva; 2010.

28. Bull FC, Al-Ansari SS, Biddle S, Borodulin K, Buman MP, Cardon G, et al. World Health Organization 2020 guidelines on physical activity and sedentary behaviour. Br J Sports Med. 2020;54(24):1451–62.

29. Buchholz AC, McGillivray CF, Pencharz PB. Physical activity levels are low in free-living adults with chronic paraplegia. Obes Res. 2003;11(4):563–70.

30. Janssen TWJ, Van Oers CAJM, Veeger HEJ, Hollander AP, Van Der Woude LHV, Rozendal RH. Relationship between physical strain during standardised ADL tasks and physical capacity in men with spinal cord injuries. Paraplegia. 1994;32(12):844–59.

31. Tweedy SM, Beckman EM, Geraghty TJ, Theisen D, Perret C, Harvey LA, et al. Exercise and Sports Science Australia (ESSA) Position Statement on exercise and spinal cord injury. J Sci Med Sport. 2017;20(5):422–3. [doi:10.1016/j.jsams.2016.02.001]

32. Martin Ginis KA, van der Scheer JW, Latimer-Cheung AE, Barrow A, Bourne C, Carruthers P, et al. Evidence-based scientific exercise guidelines for adults with spinal cord injury: an update and a new guideline. Spinal Cord [Internet]. 2018;56(4):308–21. [doi:10.1038/s41393-017-0017-3]

33. World Health Organization. Nutrition. [cited 2022 Feb 23]. URL: https://www.who.int/health-topics/nutrition

34. World Health Organization. Healthy diet. 2020.

35. World Health Organization. Obesity and Overweight. 2021 [cited 2022 Feb 23]. URL: https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight

36. Hill JO, Commerford R. Physical Activity , Fat Balance , and Energy Balance. Int J Sport Nutr. 1996;6:80–92.

37. Muscogiuri G, Barrea L, Annunziata G, Di Somma C, Laudisio D, Colao A, et al. Obesity an sleep disturbance: the chicken or the egg? Critial Rev Food Sci Nutr. 2019;59(13):2158–65.

38. Lieberman J, Goff D, Hammond F, Schreiner P, Norton HJ, Dulin M, et al. Dietary intake and adherence to the 2010 Dietary Guidelines for Americans among individuals with chronic spinal cord injury: A pilot study. J Spinal Cord Med. 2014;37(6):751–7.

39. Mukherjee S, Patel SR, Kales SN, Ayas NT, Strohl KP, Gozal D, et al. An official American Thoracic Society Statement: The Importance of Healthy Sleep. Am J Respir Crit Care Med. 2015;191(12):1450–8.

40. Zielinski MR, Mckenna JT, Mccarley RW. Functions and Mechanisms of Sleep. AIMS Neurosci. 2016;3(April):67–104.

41. Frank E, Sidor MM, Gamble KL, Cirelli C, Sharkey KM, Hoyle N, et al. Circadian clocks, brain function, and development. Ann N Y Acad Sci. 2013;1306:43–67.

42. Xie L, Kang H, Xu Q, Chen MJ, Liao Y, Thiyagarajan M, et al. Sleep Drives Metabolite Clearence from the Adult Brain. Science (80-). 2013;342(6156):373–7.

43. Leung V, Colantonio A, Santaguida PL. Wheelchair use, pain, and satisfaction with life in a national sample of older adults. Gerontechnology. 2005;3(3).

44. Sarraf P, Azizi S, Moghaddasi AN, Sahraian MA, Tafakhore A, Ghajarzadeh M. Relationship between Sleep Quality and Quality of Life in Patients with Multiple Sclerosis. Int J Prev Med. 2014;5(12):1582–6.

45. Taheri S, Lin L, Austin D, Young T, Mignot E. Short Sleep Duration is Associated with Reduced Leptin, Elevated Ghrelin, and increased Body Mass Index. PLoS Med. 2004;1(3).

46. Brondel L, Romer MA, Nougues PM, Touyarou P, Davenne D. Acute partial sleep deprivation increases food intake in healthy men. Am J Clin Nutr. 2010;91(6):1550–9.

47. Patel SR, Malhotra A, White DP, Gottlieb DJ, Hu FB. Association between Reduced Sleep and Weight Gain in Women. Am J Epidemiol. 2006;164(10):947–54.

48. Laricchia F. Wearables - Statistics & facts. February 3. 2022 [cited 2022 Feb 28]. URL: https://www.statista.com/topics/1556/wearable-technology/#dossierKeyfigures

49. Grigorean VT, Sandu AM, Popescu M, Iacobini MA, Stoian R, Neascu C, et al. Cardiac dysfunctions following spinal cord injury. J Med Life. 2009;2(2):133–45.

50. Grimm DR, DeMeersman RE, Garofano RP, Spungen AM, Bauman WA. Effect of provocative maneuvers on heart rate variability in subjects with quadriplegia. Am J Physiol - Hear Circ Physiol. 1995;268.

51. eHealth Health Task Force. Redesigning Health in Europe for 2020. 2012.

52. RIVM. Sustainable care and prevention. [cited 2022 Mar 17]. URL: https://www.rivm.nl/en/about-rivm/knowledge-and-expertise/strategic-programme-rivm/2019-2022/sustainable-care-and-prevention

53. Edington DW, Schultz AB. The Future of Health Promotion in the 21st Century : A Focus on the Working Population. Am J Lifestyle Med. 2016;10(4):242–52.

54. Boulos MNK, Wheeler S, Tavares C, Jones R. How smartphones are changing the face of mobile and participatory healthcare: An overview, with example from eCAALYX. Biomed Eng Online. 2011;10(1):24.

55. Paglialonga A, Mastropietro A, Scalco E, Rizzo G. The mHealth. In: Andreonie G, Perego P, Frumento E, editors. mHealth current and future applications. Trento, Italy: Springer; 2019. p. 5–17.

56. Ritterband LM, GonderFrederick LA, Cox DJ, Clifton AD, West RW, Borowitz SM. Internet interventions: In review, in use, and into the future. Prof Psychol Res Pract. 2003;34:527–34.

57. van den Akker LE, Holla JFM, Dadema T, Visser B, Valent LJ, de Groot S, et al. Determinants of physical activity in wheelchair users with spinal cord injury or lower limb amputation: perspectives of rehabilitation professionals and wheelchair users. Disabil Rehabil. 2020;42(14):1934-1941. [doi:10.1080/09638288.2019.1577503]

58. Holla JFM, van den Akker LE, Dadema T, de Groot S, Tieland M, Weijs PJM, et al. Determinants of dietary behaviour in wheelchair users with spinal cord injury or lower limb amputation: Perspectives of rehabilitation professionals and wheelchair users. PLoS One. 2020;15(1).

59. Rehman H, Kamal AK, Morris PB, Sayani S, Merchant AT, Virani SS. Mobile heath (mHealth) technology for the management of hypertension and hyperlipidemia: slow start but loads of potential. Curr Atheroscler Rep. 2017;19(3).

60. Kim BY, Lee J. Smart Devices for Older Adults Managing Chronic Disease: A Scoping Review. JMIR mHealth uHealth. 2017;5(5).

61. Fjeldsoe B, Neuhaus M, Winkler E, Eakin E. Systematic Review of Maintenance of Behavior Change Following Physical Activity and Dietary Interventions. Heal Psychol. 2011;30(1):99–109.

62. Bardus M, van Beurden SB, Smith JR, Abraham C. A review and content analysis of engagement, functionality, aesthetics, information quality, and change techniques in the most popular commercial apps for weight management. Int J Behav Nutr Phys Act. 2016;13(1). [doi:10.1186/s12966-016-0359-9]

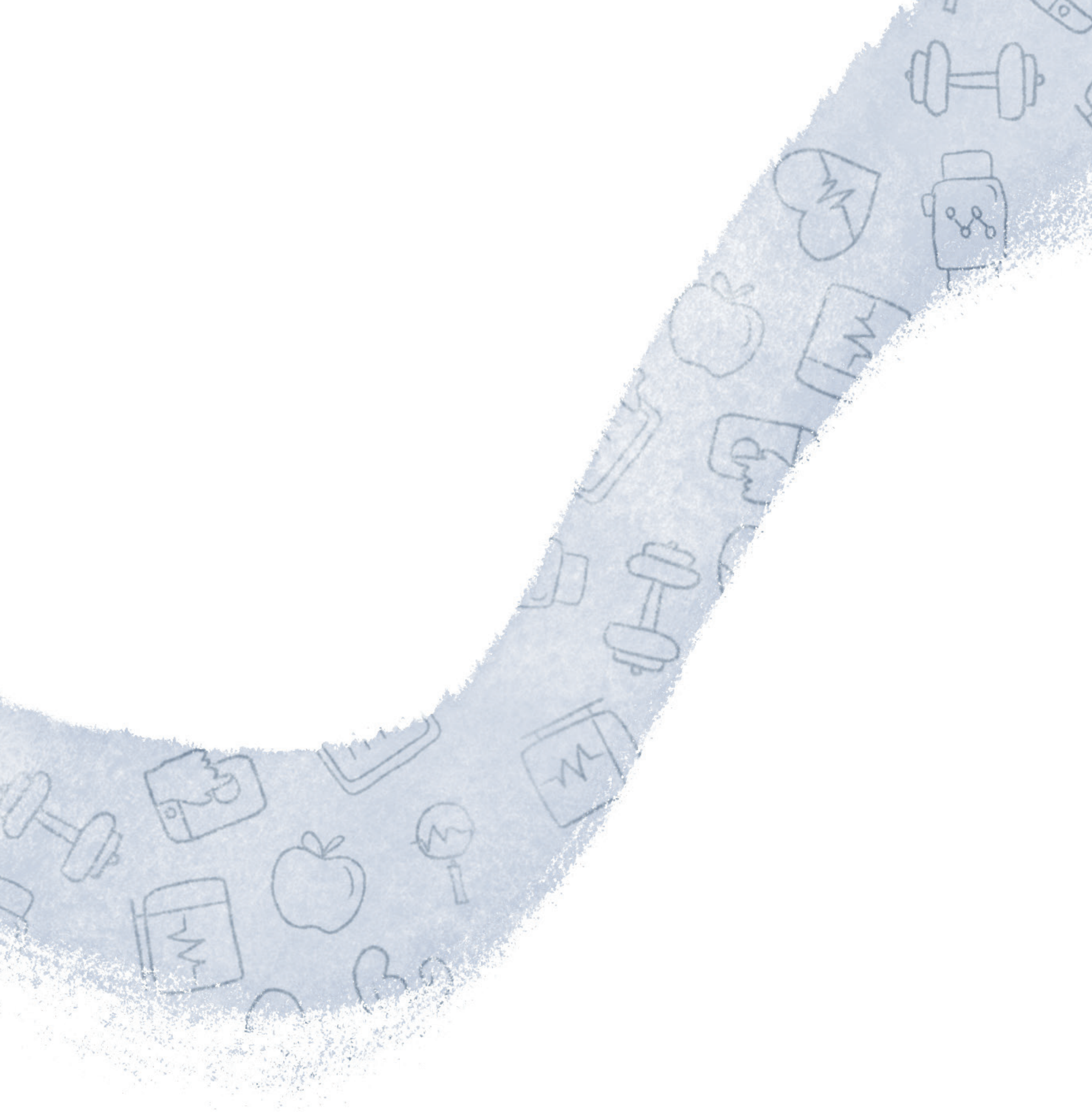
63. Ritterband LM, Thorndike FP, Cox DJ, Kovatchev BP, Gonder-frederick LA. A Behavior Change Model for Internet Interventions. Ann Behav Med. 2009;38:18–27.

64. Mercer K, Li M, Giangregorio L, Burns C, Grindrod K. Behavior Change Techniques Present in Wearable Activity Trackers: A Critical Analysis. JMIR mHealth uHealth. 2016;4(2).

65. Lyons EJ, Lewis ZH, Mayrsohn BG, Rowland JL. Behavior Change Techniques Implemented in Electronic Lifestyle Activity Monitors: A Systematic Content Analysis. J Med Internet Res. 2014;16(8).

66. Ogbanufe O, Gerhart N. Watch It! Factors Driving Continued Feature Use of the Smartwatch. Int J Human–Computer Interact. 2018;34(11):999–1014. [doi:10.1080/10447318.2017.1404779]

67. Mateo GF, Granado-Font E, Ferré-Grau C, Montana-Carreras X. Mobile phone apps to promote weight loss and increase physical activity: a systematic review and meta-analysis. J Med Internet Res. 2015;17(11).



Chapter 2

Associations between meeting Exercise Guidelines, Physical Fitness and Health in People with Spinal Cord Injury

Published as: Hoevenaars D, Holla JFM, Postma K, van der Woude LHV, Janssen TWJ, de Groot S. Associations between meeting exercise guidelines, physical fitness, and health in people with spinal cord injury. Disability and Rehabilitation 2022.

Abstract

Purpose: (1) To estimate the proportion of Dutch wheelchair users with spinal cord injury (SCI) who meet different SCI exercise guidelines; (2) to evaluate which demographic and lesion characteristics are associated with meeting these guidelines; (3) whether meeting these guidelines is associated with physical fitness and health.

Materials and methods: Based on the PASIPD questionnaire items, participants were allocated to meeting two SCI aerobic exercise guidelines, which differ in exercise load. Differences in personal, lesion, fitness, and health characteristics between groups were tested with a one-way ANOVA. Multiple regression analyses were performed to evaluate if meeting guidelines was associated with better fitness and health. Statistical significance was accepted at $p < 0.05$.

Results: Of the 358 included participants, 63.1% met at least one aerobic exercise guideline. Being female, older age, having tetraplegia, and lower educational level were associated with a lower likelihood to meet the aerobic exercise guidelines. Meeting aerobic exercise guidelines showed a positive association with all respiratory and exercise capacity parameters. Limited associations were found between meeting exercise guidelines and health.

Conclusions: Meeting exercise guidelines was associated with better respiratory functions and exercise capacity with additional fitness and some body composition benefits in higher exercise activity levels.

Keywords: Spinal cord injury; exercise guidelines; health; physical activity; physical fitness.

Implications for rehabilitation: Meeting SCI exercise guidelines are associated with better respiratory functions and exercise capacity with additional fitness and body composition benefits when exercising at higher activity levels, emphasizing the value and importance of regular exercise in individuals with SCI.

Introduction

Being physically active has many potential benefits, such as reduced risks of cardiovascular disease and other noncommunicable diseases, increased mental health, and weight control [1]. However, despite these well-known benefits of physical activity (PA), 31% of the abled-bodied adults globally and 43% in Western countries are physically inactive [2]. These numbers are even higher in people with spinal cord injury (SCI), who are 60% less physically active compared to able-bodied individuals [3]. PA promotion is therefore needed and of great importance, especially in people with SCI.

To facilitate PA promotion, the World Health Organization (WHO) developed evidence-based PA guidelines based on studies on the dose-response relationship between frequency, duration, and intensity of physical activity and health outcomes [4,5]. Although the WHO states "the recommendation can be applied to adults with disabilities," it is also mentioned that "they may need to be adjusted for each individual based on their exercise capacity and specific health risks or limitations" [4]. Despite the effort to place more emphasis on people with chronic disabilities in the new 2020 WHO PA guidelines, limited evidence was presented on specific chronic conditions and disabilities [5]. Therefore, the two recently developed and published exercise guidelines specifically for people with SCI to promote PA are relevant [6,7]. Both guidelines were specifically designed towards exercise, a subcategory of PA, which is considered as "physical activity that is planned, structured, repetitive, and purposive in the sense that improvement or maintenance of one or more components of physical fitness is an objective" [8]. Therefore, the focus of the remaining of this paper will be on exercise specifically.

The recent exercise guidelines for people with SCI [6,7] are to a certain extent similar but seem to differ in recommended weekly aerobic exercise, as shown in Table 1. Martin Ginis et al. [6] developed SCI-specific exercise guidelines for improving fitness with additional guidelines with more strenuous recommendations for improving cardiometabolic health. The guidelines developed by Tweedy et al. [7] are based on the assumption that the recommendations for the general population also apply to people with SCI, as SCI-specific exercise evidence is consistent with those from the general population. Therefore, the Tweedy et al. [7] guidelines resulted in a higher physical weekly load regarding frequency and time than the guidelines of Martin Ginis et al. [6]. According to Tweedy et al. [7], this higher load is "required in order for people with SCI to achieve good cardiometabolic health, physical fitness, and functioning."

These differences in load between the exercise guidelines likely influence the proportion of the SCI community meeting them. Rauch et al. [9] documented that sex, age, time since injury (TSI), severity of SCI, and type of locomotion are associated with meeting WHO exercise guidelines, and Rocchi et al. [10] documented that type of locomotion and autonomous motivation are associated with meeting the guidelines of Martin Ginis. It remains unknown, however, if and how meeting different exercise guidelines and therefore weekly load, translates to additional fitness and health benefits [11]. With increasing exercise levels, and therefore, increasing fitness levels, a curvilinear reduction in mortality has been well documented in able-bodied [12]. As a consequence, it could be assumed that physical fitness and health are more likely to be better in people who meet the more strenuous guidelines of Tweedy et al. [7], compared to people who only meet the fitness or cardiometabolic guidelines of Martin Ginis et al. [6] or people not meeting any exercise guidelines at all.

Therefore, the aims of this study were: (1) to estimate the proportion of Dutch wheelchair users with chronic SCI (≥5 years after injury) meeting two different exercise guidelines; (2) to evaluate which demographic and lesion characteristics are associated with meeting these guidelines; and (3) whether meeting these guidelines is associated with better physical fitness and health.

Table 1. Overview of different SCI exercise guidelines.

	Aerobic exercise Weekly time spent in minutes in intensity					Strength exercise Frequency per week	
Exercise guidelines	**Moderate**	**Or**	**Vigorous**	**Or**	**Combination of moderate/ vigorous**	**And**	**3 sets of each major muscle group**
Martin Ginis fitness	40		40		40		2
Martin Ginis cardiometabolic	90		90		90		2
Tweedy	150		60		150/60		2

Methods

Study Design

A cross-sectional analysis was performed on merged data from two Dutch research programs, i.e., “Restoration of mobility in the rehabilitation of persons with SCI” (Umbrella project) [13] and “Active LifestyLe Rehabilitation Interventions in aging Spinal Cord injury” (ALLRISC) [14]. Participants were recruited from eight Dutch rehabilitation centers with a specialized SCI unit. All participants provided informed consent after being informed about the study. Approval was given by the local medical ethics committee of rehabilitation center Hoensbroek and the medical ethics committee of the University Medical Centre Utrecht for the Umbrella project and by the medical ethics committee of the University Medical Centre Utrecht for the ALLRISC project.

Participants

Individuals were eligible to participate in the Umbrella project if they had a recent SCI, classified as A-D on the American Spinal Injury Association (AISA) impairment scale [15]; were aged between 18 and 65 years; and were wheelchair dependent for community use. Exclusion criteria to participate were: having an SCI due to malignancies; progressive disease; known cardiovascular disease or psychiatric problems; and insufficient command of the Dutch language. The data of the Umbrella project collected 5 years after the discharge of inpatient rehabilitation were analyzed for this study [16]. Individuals were eligible to participate in the cross-sectional ALLRISC project if they had an SCI, age at injury between 18 and 35 years with at least a time since injury (TSI) of 10 years at inclusion; and were wheelchair dependent for longer distances (>500m). Insufficient command of the Dutch language was an exclusion criterion to participate in this project [14].

Data collection

The two datasets were prepared and merged on all available parameters relating to personal demographics, lesion characteristics, Physical Activity Scale for Individuals with Physical Disabilities (PASIPD) items, fitness, and health-related outcomes. All participants who did not complete items 4–6 from the PASIPD, needed to determine whether exercise guidelines were met or not, were excluded from the analysis.

Physical activity

Three items (items 4–6) from the PASIPD [17], administered in both projects, were used to determine whether participants met the different SCI-specific exercise guidelines. These items determined the weekly amount of time spent in moderate (item 4) and strenuous (item 5) exercise intensity and on muscle strength exercises (item 6). For each item, the frequency (0, 1–2, 3–4, or 5–7 times a week) and duration (<1, 1–2, 2–4, >4h) were reported. This could then be calculated into an average daily time spent (hours/day) on the aerobic exercise of moderate intensity, vigorous intensity, and strength exercise, based on the algorithm the PASIPD provided [17], and converted into weekly average time spent on each activity. PASIPD outcomes were checked on outliers, by comparing the results to answers of other exercise-related available questions (e.g., hours per week spent on sports participation). When the PASIPD outcomes were not in line with the other exercise-related statements, the participant was excluded from the dataset due to unreliable PASIPD outcomes.

Based on the remaining PASIPD outcomes it was determined whether participants met any aerobic part of any SCI-specific exercise guidelines, with exercise frequency not taken into account. Participants whose weekly time spent on moderate exercise exceeded 150min or on vigorous exercise exceeded 60min, were categorized as meeting the exercise guidelines of Tweedy et al. [7] (TW guidelines). A combination of time spent on moderate and vigorous exercise intensity was also allowed to meet the TW guidelines. Time spent on vigorous exercise multiplied by 2.5 was summed with time spent on moderate intensity and should have exceeded the recommended 150min. Participants whose weekly time spent on moderate and/or vigorous exercise exceeded 90min were categorized as meeting the cardiometabolic exercise guidelines of Martin Ginis et al. [6] (MG cardiometabolic guidelines). Participants whose weekly time spent on moderate and/or vigorous exercise exceeded 40min were categorized as meeting the fitness exercise guidelines of Martin Ginis et al. [6] (MG fitness guidelines). If participants did not reach the recommended weekly 40min, they were categorized as not meeting any guidelines.

Item 6 was used to determine whether individuals were involved in strength exercises at least once a week, as the questionnaire only allows to differentiate frequency into either never, 1–2 times, 3–4 times, or 5–7 times a week. Based on these outcomes, participants were categorized into either: (1) not involved in any strength exercise, or (2) involved in strength exercise at least once a week, which was also done in the study of Rauch et al. [9].

Groups meeting Guidelines or not

To test how meeting different exercise guidelines influences fitness and health, participants were allocated to one of the following four groups: (1) not meeting any exercise guidelines; (2) meeting the MG fitness guidelines; (3) meeting the MG cardiometabolic guidelines; or (4) meeting the TW guidelines. Allocation to the different guideline groups was done as described in Table 1. Participants meeting multiple exercise guidelines were only allocated to the most strenuous exercise guidelines in the order as described above with the TW guideline being the most strenuous.

Demographics

Personal and social demographics (sex, age, height, educational level) were collected. Educational level was categorized into three categories according to the Dutch central agency for statistics [18]: (1) lower educational level (primary school, lower educational level), (2) middle educational level (high school, vocational education), and (3) higher educational level (applied-university or higher).

SCI Characteristics

SCI characteristics (TSI, etiology, lesion level, motor, and sensory completeness) were collected and assessed according to the International Standards for Neurological Classification of Spinal Cord Injury [15]. Neurological lesion level below T1 was considered as paraplegia and lesions at or above T1 as tetraplegia. The etiology of the SCI was dichotomized into either traumatic or non-traumatic.

Fitness

Respiratory Function

Respiratory function was tested and measured according to a standardized protocol [19] with the following outcomes: forced vital capacity (FVC), forced expiratory volume in 1s (FEV1), forced inspiratory volume in 1s (FIV1), forced expiratory flow (PEF) and forced inspiratory flow (PIF). All measurements were repeated until at least three measurements of each test within a range of ±5% were recorded. The highest measured outcome value of each test was used for analysis.

Exercise Capacity

To test exercise capacity, a graded wheelchair exercise test was performed with the outcome measures peak oxygen uptake (VO2peak) expressed in L/min and L/kg/min and peak power output (POpeak) expressed in Watt (W) and W/kg. Participants were excluded from this test if they had (1) cardiovascular contraindications as stated by the American College of Sports Medicine guidelines [20] or (2) severe musculoskeletal complaints in the upper extremities. The equipment and protocol used for this test have been described in detail elsewhere [16,21]. VO2peak was determined by using the highest recorded values of the average oxygen consumption during 30-s periods. POpeak was the power output measured during the highest treadmill inclination that was maintained by the participant for at least 30s.

Health

Body mass (kg) and height (m) were measured and used to calculate the body mass index (BMI) (body mass/height^2). In the ALLRISC project only, waist circumference (WC, in cm) was measured three times using a tape measure, with the average value being used for analysis. Systolic (SBP) and diastolic blood pressure (DBP) were measured in mmHg in a seated position by a physician with an automatic (ALLRISC project) or manual sphygmomanometer (Umbrella project). Hypertension was defined as SBP of ≥140mmHg and/or DBP of ≥90mmHg [22]. Mean arterial pressure (MAP) was calculated by the following formula: DBP + 1/3*(SBP - DBP). Lipid profile was determined from blood samples taken in the morning in a fasting state. Concentrations (mmol/L) of total cholesterol (TC), high-density lipoprotein (HDL), low-density lipoprotein (LDL), and triglycerides (TG) were determined, and TC/HDL calculated. Standardized laboratory protocols were used to obtain the concentrations.

Statistics

IBM SPSS software (Version 27, IBM Corporation, Armonk, NY, USA) was used for analyses. The total study population and the categorized groups based on meeting different SCI-specific exercise guidelines were described. Differences in personal, lesion, fitness, and health characteristics between selected groups were tested with a one-way ANOVA. If the assumptions were violated, the non-parametrical equivalent test was used. All categorical data were tested with the Kruskal-Wallis test. Dichotomous data were tested with the Chi-Square test. In the case of significance of the one-way ANOVA test, a *post-hoc* Bonferroni test was performed among all groups with the significance level set at $p<0.05$. In the case of significance of the non-parametrical alternative, a corresponding *post-hoc* test was performed among all three groups, with a significance level set on $p<0.017$ to adjust for alpha inflation (0.05/3=0.017).

Multiple regression analysis was performed to evaluate if meeting SCI-specific aerobic exercise guidelines affects fitness and health. Multiple regressions were performed twice on each fitness and health outcome variable. Once with the MG guidelines group and once with the inactive group as the reference category to allow for multiple comparisons. In the case of dichotomous outcomes, logistic regressions were performed. Outcomes were adjusted for the potential confounders age, sex, TSI, lesion level, lesion completeness, etiology of SCI, and educational level. Statistical significance was considered if one of the two group variables showed $p<0.05$ compared to the reference category and confidence intervals are presented in Supplementary Appendix 1.

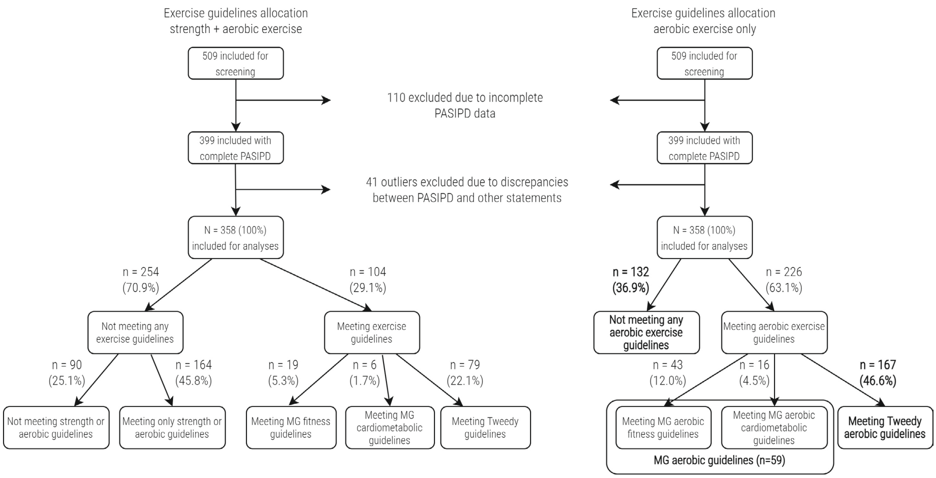


Figure 1. Flowchart of in- and exclusion of data and of group allocation of different SCI exercise guidelines. Bolded groups were used for group comparisons and multiple regression analysis.

Results

A total of 358 participants were included for analysis after excluding 151 participants. The in-/exclusion of participants, and exercise guidelines allocation process, including when strength exercise was taken into account, is depicted in Figure 1. The MG cardiometabolic group (*n*=16) was merged with the MG fitness group (*n*=43) during the group comparisons and regression analyses to ensure decent groups size and is from here onwards referred to as the MG guidelines (*n*=59). Personal, lesion, fitness, and health characteristics, including the number of participants available for each variable and guidelines allocation, are shown in Table 2. Outcomes for each group separately and group comparisons after allocation based on meeting SCI aerobic exercise guidelines are presented in Table 3. Several variables showed significant differences between the groups. Being female, older in age, having tetraplegia, and having a lower educational level was associated with a lower likelihood to meet any exercise guidelines (Table 3). All fitness variables showed more positive outcomes in individuals meeting exercise guidelines compared to inactive individuals, of which multiple variables showed a significant difference. However, no significant differences between groups were found for health-related variables except for waist circumference. TW guidelines group showed a significantly smaller waist circumference compared to the inactive group (Table 3).

Physical Fitness

Respiratory Function

In all multiple regressions, outcomes were adjusted for demographic and lesion characteristics. All respiratory parameters were significantly higher ($p \leq 0.005$; Table 4) in individuals meeting the MG guidelines compared to the inactive group, except for the PIF. The TW guidelines group showed significantly better scores ($p<0.001$) on all respiratory parameters compared to the inactive group (Table 4). No significant differences in respiratory parameters were found between the MG and TW guidelines groups, except for PIF, which was higher in the TW guidelines group ($p=0.009$; Table 4b, Supplementary Appendix 1).

Exercise Capacity

The TW guidelines group showed a significantly higher relative VO2peak ($p<0.001$, Table 4) and absolute VO2peak ($p<0.001$, Table 5a, Supplementary Appendix 1) compared to the inactive group. Both the MG ($p=0.047$) and the TW guidelines group ($p<0.001$) scored significantly better on relative POpeak compared to the inactive group (Table 4). The TW guidelines group scored significantly higher (<0.001) on absolute POpeak compared to the inactive group (Table 5a, Supplementary Appendix 1). Additionally, the TW guidelines group scored significantly better on both absolute VO2peak ($p=0.022$) and POpeak ($p=0.026$) compared to the MG guidelines group (Table 5b, Supplementary Appendix 1).

Table 2. Demographic, lesion, fitness, and health characteristics of all participants (*N*=358).

Demographic characteristics	n	Frequency (%) / Mean (SD)
Sex (male)	358	262 (73.2%)
Age (years)	358	47.4 (10.8)
Height (m)	336	1.79 (0.10)
Body mass (kg)	339	82.1 (17.2)
Educational level	337	
Lower educational level		76 (22.6%)
Middle educational level		113 (33.5%)
Higher educational level		148 (43.9%)
Lesion characteristics		
TSI (years)	357	18.5 (11.2)
Etiology of SCI (traumatic)	358	310 (86.6%)
Lesion level (paraplegia)	358	189 (52.8%)
Lesion Completeness (motor complete)	358	278 (77.7%)
Guideline allocation		
Meeting aerobic exercise guidelines	358	
Not meeting any exercise guidelines		132 (36.9%)
Meeting MG fitness guidelines		43 (12.0%)
Meeting MG cardiometabolic guidelines		16 (4.5%)
Meeting TW guidelines		167 (46.6%)
Performs strength exercise at least once a week	358	146 (40.8%)
Fitness characteristics		
FVC (L)	329	3.91 (1.27)
FEV1 (L)	330	3.16 (0.98)
FIV1 (L)	319	3.38 (1.13)
PEF (L/s)	330	6.41 (2.22)
PIF (L/s)	326	5.06 (1.79)
VO_2peak (L/min)	201	1.34 (0.53)
VO_2peak (ml/kg/min)	201	16.82 (6.64)
POpeak (W)	185	50.6 (25.3)
POpeak (W/kg)	184	0.64 (0.31)
Health characteristics		
BMI (kg/m^2)	333	25.6 (5.0)
Waist circumference (cm)	218	98.1 (15.0)
SBP (mmHg)	327	124 (24)
DBP (mmHg)	327	76 (14)
MAP (mmHg)	327	92 (17)
Hypertension (yes)	327	100 (30.6%)
Total cholesterol (mmol/L)	278	4.85 (0.99)
HDL (mmol/L)	278	1.20 (0.37)

Table 2. Continued from previous page.

Demographic characteristics	n	Frequency (%) / Mean (SD)
Cholesterol/HDL ratio	278	4.34 (1.40)
LDL (mmol/L)	272	3.03 (0.86)
TG (mmol/L)	276	1.59 (1.14)

Health

A significantly lower BMI was found (p=0.039) in the MG guidelines group compared to the inactive group (Table 4). A significantly lower WC was found (p=0.007) in the TW guidelines group compared to the inactive group (Table 4). The TW guidelines group showed significantly higher SBP (p=0.005, Table 6a, Supplementary Appendix 1) and MAP (p=0.026, Table 4) compared to the inactive group. No significant differences in the prevalence of hypertension or in lipid profile outcomes were found among groups.

Table 3. Differences in demographic and lesion characteristics, fitness, and health outcomes between groups meeting different aerobic exercise guidelines.

	Not meeting aerobic exercise guidelines (n=132)		Meeting MG aerobic guidelines (n=59)		Meeting TW aerobic guidelines (n=167)		
Demographic characteristics	**n**	**n or mean (SD)**	**n**	**n or mean (SD)**	**n**	**n or mean (SD)**	**p value**
Sex (f/m)	131	42 / 89[b]	59	22 / 37	167	30 / 136[b]	.016[a]
Age (years)	132	50.0 (11.0)[b]	59	47.3 (11.4)	167	45.4 (10.1)[b]	.001
Height (m)	123	1.77 (0.11)[b]	54	1.80 (0.10)	159	1.81 (0.09)[b]	.005
Body mass (kg)	125	82.7 (17.6)	55	80.4 (16.7)	159	82.2 (17.2)	.713
Education level (low/middle/high)	122	33 / 44 / 45[b]	56	19 / 17 / 20[c]	159	24 / 52 / 83[b,c]	.003[a]
Lesion characteristics							
TSI (years)	131	20.0 (12.1)	59	17.5 (10.6)	167	17.4 (10.5)	.209[a]
Etiology (traumatic/non-traumatic)	132	107 / 25[b]	59	51 / 8	167	152 / 15[b]	.043[a]
Lesion level (PP/TP)	131	56 / 75[b]	59	30 / 29	167	103 / 64[b]	.015[a]
Lesion completeness (motor complete / incomplete)	132	102 / 30	59	43 / 16	167	133 / 34	.559[a]
Fitness characteristics							
FVC (L)	120	3.37 (1.31)[b,d]	53	4.17 (1.13)[d]	156	4.24 (1.14)[b]	<.001
FEV1 (L)	120	2.76 (1.03)[b,d]	51	3.30 (0.87)[d]	157	3.41 (0.87)[b]	<.001
FIV1 (L)	116	2.93 (1.07)[b,d]	53	3.50 (1.03)[d]	152	3.68 (1.10)[b]	<.001
PEF (L/s)	120	5.58 (2.35)[b,d]	52	6.67 (1.88)[d]	157	6.97 (2.03)[b]	<.001[a]
PIF (L/s)	118	4.49 (1.63)[b]	52	4.80 (1.34)[c]	156	5.59 (1.88)[b,c]	<.001
VO_2peak (L/min)	42	1.17 (0.45)[b]	40	1.20 (0.40)[c]	119	1.44 (0.57)[b,c]	.003
VO_2peak (ml/kg/min)	42	14.1 (4.4)[b]	40	15.6 (5.8)	119	18.2 (7.2)[b]	.001
POpeak (W)	38	40.8 (21.8)[b]	31	42.9 (19.2)[c]	116	56.0 (26.3)[b,c]	.001
POpeak (W/kg)	38	0.50 (0.24)[b]	31	0.56 (0.26)	115	0.70 (0.32)[b]	.001
Health characteristics							
BMI (kg/m^2)	123	26.4 (5.8)	53	24.8 (4.4)	157	25.1 (4.5)	.097[a]
Waist circumference (cm)	78	102.1 (17.6)[b]	36	97.7 (13.2)	104	95.3 (12.9)[b]	.011
SBP (mmHg)	116	122 (24)	55	123 (27)	156	126 (22)	.329
DBP (mmHg)	116	76 (15)	55	75 (16)	156	77 (14)	.710
MAP (mmHg)	116	91 (17)	55	91 (18)	156	93 (16)	.566
Hypertension (yes / no)	116	32 / 84	55	18 / 37	156	50 / 106	.681
Total cholesterol (mmol/L)	106	4.83 (1.13)	42	5.09 (0.89)	130	4.78 (0.89)	.209
HDL (mmol/L)	106	1.19 (0.41)	42	1.27 (0.33)	130	1.18 (0.35)	.277[a]
Cholesterol / HDL ratio	106	4.37 (1.42)	42	4.23 (1.12)	130	4.36 (1.46)	.964[a]
LDL (mmol/L)	105	3.06 (0.96)	42	3.20 (0.81)	125	2.94 (0.77)	.214
TG (mmol/L)	104	1.53 (1.01)	42	1.51 (0.74)	130	1.66 (1.34)	.772[a]
Strength training							
Performs strength exercises at least once a week (yes/no)	132	42 / 90[b]	53	25 / 28	167	79 / 88[b]	.025[a]

[a]Indicates the use of a non-parametric alternative. Post-hoc non-parametrical test significance accepted at $P < .017$.

[b]Significant difference between inactive and TW.

[c]Significant difference between MG and TW.

[d]Significant difference between Inactive and MG.

Table 4. Multiple regression analysis on fitness and health outcomes with inactive as reference.

Variables included in the model	FVC		FEV1		FIV1		PEF		PIF	
	B (SE)	P	B (SE)	P	B (SE)	P	B (SE)	P	B (SE)	P
Constant	3.90 (.35)	<.001	3.44 (.27)	<.001	3.18 (.32)	<.001	5.14 (.65)	<.001	4.84 (.53)	<.001
MG guidelines vs. inactive	.74 (.19)	<.001	.46 (.14)	.001	.51 (.17)	.003	.98 (.35)	.005	.15 (.28)	.603
TW guidelines vs. inactive	.67 (.14)	<.001	.45 (.11)	<.001	.59 (.13)	<.001	1.12 (.27)	<.001	.87 (.22)	<.001
Potential confounders										
Sex	.48 (.10)	<.001	.33 (.08)	<.001	.38 (.09)	<.001	.61 (.19)	.001	.42 (.15)	.006
Age	-.02 (.01)	.002	-.02 (.01)	<.001	-.01 (.01)	.045	-.02 (.01)	.082	-.03 (.01)	.028
Lower educational level vs. middle	.20 (.17)	.263	.14 (.13)	.299	.08 (.16)	.607	.45 (.32)	.163	.09 (.27)	.746
Higher educational level vs. middle	.10 (.15)	.504	.10 (.11)	.395	.04 (.14)	.785	.45 (.27)	.099	.08 (.22)	.735
TSI	-.003 (.01)	.688	-.002 (.01)	.691	-.003 (.01)	.601	.01 (.01)	.309	.01 (.01)	.360
Etiology SCI	-.07 (.20)	.716	-.22 (.16)	.163	-.11 (.18)	.565	-.39 (.38)	.305	-.29 (.31)	.352
Lesion level	.38 (.09)	<.001	.29 (.07)	<.001	.35 (.08)	<.001	.71 (.17)	<.001	.53 (.14)	<.001
Lesion completeness	.57 (.16)	<.001	.46 (.12)	<.001	.46 (.15)	.002	.75 (.29)	.012	.20 (.24)	.426
	Relative VO2peak		**Relative POpeak**		**WC**		**BMI**		**MAP**	
	B (SE)	**P**	**B (SE)**	**P**	**B (SE)**	**P**	**B (SE)**	**P**	**B (SE)**	**P**
Constant	16.26 (2.71)	<.001	.58 (.12)	<.001	88.02 (7.87)	<.001	21.39 (1.62)	<.001	65.20 (5.21)	<.001
MG guidelines vs. inactive	2.46 (1.45)	.091	.14 (.07)	.047	-3.41 (3.07)	.268	-1.79 (.86)	.039	1.90 (2.67)	.476
TW guidelines vs. inactive	4.49 (1.20)	<.001	.25 (.06)	<.001	-6.36 (2.34)	.007	-.92 (.66)	.162	4.65 (2.08)	.026
Potential confounders										
Sex	1.03 (.63)	.105	.04 (.03)	.158	9.87 (2.51)	<.001	.42 (.37)	.255	.16 (2.10)	.941
Age	-.13 (.06)	.033	-.01 (.003)	.010	.09 (.23)	.688	.10 (.03)	.003	.37 (.11)	.001
Lower educational level vs. middle	1.61 (1.40)	.250	.03 (.06)	.623	-2.30 (3.14)	.465	.15 (.80)	.851	.83 (2.48)	.738
Higher educational level vs. middle	.56 (1.10)	.611	.06 (.05)	.230	-1.47 (2.65)	.580	.47 (.68)	.492	1.28 (2.13)	.548
TSI	.004 (.06)	.940	.002 (.003)	.345	.13 (.22)	.554	-.03 (.03)	.345	.13 (.10)	.198
Etiology SCI	-.21 (1.64)	.900	.12 (.08)	.132	4.72 (3.75)	.209	-.37 (.94)	.695	2.77 (2.89)	.338
Lesion level	2.61 (.60)	<.001	.12 (.03)	<.001	-.56 (1.31)	.669	.15 (.42)	.717	5.54 (1.30)	<.001
Lesion completeness	-.34 (1.25)	.788	-.11 (.06)	.069	.003 (2.81)	.999	.35 (.73)	.637	1.01 (2.27)	.656

The inactive group was used as reference variable in this table. Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as motor complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

Discussion

The purpose of this study was to estimate the proportion of Dutch wheelchair users with SCI meeting different SCI exercise guidelines, which demographic and lesion characteristics are associated with meeting these guidelines, and whether meeting these guidelines is associated with better physical fitness and health. Results showed that only 29% of Dutch wheelchair users with SCI meet SCI-specific exercise recommendations if strength exercise is taken into account. When strength training is not taken into account, 63% meet either the MG or TW guidelines for aerobic exercise. When adjusted for demographic and lesion characteristics, a strong association was found between aerobic exercise activity levels and beneficial outcomes on physical fitness, with more strenuous guidelines showing better outcomes on exercise capacity. Additional benefits were found regarding body composition in more strenuous aerobic exercise activity levels, and therefore possibly health. These results clearly show the importance of regular exercise and that the SCI-specific exercise guidelines partly achieve what they were designed for.

As expected, older age, being female, having tetraplegia, and low educational level seem to negatively influence exercise behavior, and therefore physical fitness and health outcomes. In this study, only 29% of the participants met the least strenuous SCI-specific exercise guidelines (MG), and 22% of the TW guidelines, when strength exercise was taken into account. This result shows that combining aerobic and strength exercise is a challenge for most Dutch wheelchair users with SCI. Higher proportions were found in Switzerland in previous research of Rauch et al. [9], who applied allocation to guidelines using a similar methodology. Rauch et al. found that 49% of persons with SCI fulfilled the WHO guidelines, including strength exercise, which are comparable guidelines to the TW guidelines. However, the WHO does not differentiate between moderate and vigorous activity levels like the TW guidelines. In contrast, a Canadian study showed much lower percentages, i.e., with only 12% meeting the MG exercise guidelines compared to 29% in this study [10]. When only aerobic exercise was taken into account, 63% of our participants met the MG guidelines, compared to 36% of the participants in a study of Rocchi et al. [10] who applied the Leisure Time Physical Activity Questionnaire for People with Spinal Cord Injury (LTPAQ-SCI). The use of a different questionnaire might have caused differences in allocating participants to meeting exercise guidelines or not, as the LTPAQ-SCI asks the exact number of days spent in different intensity levels while the PASIPD categorizes this question into: never, 1–2, 3–4, or 5–7 days. Therefore, it is more likely to overestimate the time spent in specific exercise intensities when using the PASIPD. Only 22% of our participants met the TW guidelines, which is much lower compared to the 44% of the general Dutch population who meets the comparable WHO guidelines [23]. This emphasizes once more the necessity to facilitate and support exercise in individuals with SCI.

Results of the regression analyses showed beneficial associations between meeting exercise guidelines and respiratory function, as both the MG and TW guidelines group scored significantly better on almost all respiratory function tests compared to the inactive group, even after correction for lesion level and completeness, and age. Respiratory dysfunction can have a severe impact on daily life in individuals with SCI. Increased residual lung volumes, along with a reduced ability to cough, can cause increased accumulation of secretion, increasing the risk of pulmonary infections and other complications [24]. No significant differences were found between the MG and TW guidelines group, suggesting respiratory function improvement already occurs at relatively low exercise activity levels.

Significantly higher outcomes in relative POpeak were found in the MG and TW guidelines groups compared to the inactive group. This is a valuable finding as most individuals with SCI depend on a manual wheelchair and those with a higher POpeak tend to experience a lower amount of strain in activities of daily living, are more likely to return to work, and experience a higher quality of life [25–27]. The TW guidelines group scored also significantly better on POpeak and relative VO2peak compared to the inactive group. There may have been a positive selection bias as a higher proportion of individuals with tetraplegia was found in the inactive group (56.8%) compared to the MG (49.2%) and TW (39.0%) guidelines groups. This probably explains the relatively low number of inactive individuals who performed a peak exercise test (31.8%), compared to the MG group (67.8%) and TW group (71.3%). Thus, the actual differences in physical fitness between the inactive group and the MG and TW guidelines groups might be even larger. However, even after controlling for lesion level, a clear pattern was found showing increased benefits in physical fitness with increased exercise activity levels.

One of the main reasons exercise guidelines were developed, was to provide evidence-based recommendations to support behavior that leads to fitness and health benefits and reduce health risks and mortality [5]. Obesity, high blood pressure, and high cholesterol are among the most critical risk factors [28]. Despite the known positive relationship between exercise and these factors, results in the present paper are limited. The TW guidelines group showed a significantly lower WC compared to the inactive group suggesting additional health benefits as the guidelines were designed for. Surprisingly, participants who met the MG guidelines showed a significantly lower BMI compared to the inactive group while participants who met the TW guidelines did not. This could be explained by the fact that BMI does not take body composition, and therefore, muscle mass into account. Significantly higher SBP and MAP were found in the TW guidelines group compared to the inactive group, however, this did not translate into significantly different hypertension ratios compared to other groups. No significant differences were found in lipid profile outcomes, which could be attributed to their complex regulation which is controlled by many factors, of which some cannot be influenced by exercise, or can be influenced by medication use, which was not taken into account in the analyses.

Strengths and limitations

Merging two relatively large SCI datasets made it possible to perform analysis with a relatively large group of 358 participants. However, this study also has some limitations. The PASIPD was used to determine whether exercise guidelines were met, which is a self-administered outcome and a questionnaire not specifically designed to quantify exercise time and exercise intensity precisely. Therefore, the outcomes obtained from the participants might not fully reflect their actual situation. Previous research has shown that the PASIPD tends to overestimate time spent on physical activity, which might have caused biased group allocation [29]. Additionally, answer options of the PASIPD for exercise frequency were in the ranges 0, 1–2, 3–4, or 5–7 times a week, as a result, exercising once a week could not be distinguished from exercising twice a week based on this item. Therefore, the classification of meeting or not meeting the aerobic exercise guidelines was based on total weekly time spent on exercise, leaving frequency (aerobic exercise at least twice a week) out of the process of allocation. The involvement of strength exercise could only be determined as at least once a week, like in the study of Rauch et al. [9]. Therefore, the actual number of participants meeting any of the exercise guidelines including strength exercise could be even lower. Moreover, differentiation in moderate or vigorous intensity level was done subjectively by the participants based on the given PASIPD questions, which included examples of moderate or vigorous exercise activities. Due to the severity and level of their lesion the exercise capacity of individuals with tetraplegia can be severely reduced, putting them under relatively more strain in activities of similar intensity compared to individuals with paraplegia, making exercise intensity differentiation difficult and possibly unreliable.

Conclusion

With only 29% a small proportion of the Dutch wheelchair users with SCI seem to meet an SCI exercise guidelines. The exercise guidelines seem to at least partially achieve what they are designed for. Meeting the MG guidelines was associated with improved respiratory function and exercise capacity, which is achieved with relatively low exercise levels. Increased exercise levels, like in the TW guidelines, were associated with additional fitness and body composition benefits.

Acknowledgements

We thank all involved researchers, physicians, and research assistants involved in data collection within the Umbrella and ALLRISC project.

Disclose statement

The authors declare no conflict of interest.

Funding

The Umbrella project was funded by the ZON-Mw rehabilitation program, grant number 1435.0003 and 1435.0025. The ALLRISC project was funded by the responsibility of the Netherlands Organization for Health Research and Development by "Fonds NutsOHRA", project number 89000006. The realization of this paper was funded by NWO, SIA and FAPESP under the big data sports call 2016.

Ethical approval

Ethical approval was given by the local medical ethics committee of rehabilitation center Hoensbroek and the Medical Ethics Committee of the University Medical Centre Utrecht. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Author Contributions

DH, JH, SdG, and TJ conceived and designed the research. LvdW and SdG organized and managed the data collection of both projects. KP was involved in the organization and data collection of the Umbrella project. DH cleaned and merged the datasets. DH analyzed the data with the supervision of JH, SdG, and TJ. DH wrote the paper and all authors read the paper, provided feedback, and approved the manuscript.

References

1. World Health Organization. Global Health Risks: mortality and burden of disease attributable to selected major risks. Geneva; World Health Organization; 2009.
2. Hallal PC, Andersen LB, Bull FC, Guthold R, Haskell W, Ekelund U, et al. Global physical activity levels: Surveillance progress, pitfalls, and prospects. Lancet. 2012;380(9838):247–257.
3. Van Den Berg-Emons RJ, Bussmann JB, Stam HJ. Accelerometry-based activity spectrum in persons with chronic physical conditions. Arch Phys Med Rehabil. 2010;91(12):1856–1861.
4. World Health Organization. Global recommendations on physical activity for health. Geneva; World Health Organization; 2010.
5. Bull FC, Al-Ansari SS, Biddle S, Borodulin K, Buman MP, Cardon G, et al. World Health Organization 2020 guidelines on physical activity and sedentary behaviour. Br J Sports Med. 2020;54(24):1451–1462.
6. Martin Ginis KA, van der Scheer JW, Latimer-Cheung AE, Barrow A, Bourne C, Carruthers P, et al. Evidence-based scientific exercise guidelines for adults with spinal cord injury: an update and a new guideline. Spinal Cord. 2018;56(4):308-314.
7. Tweedy SM, Beckman EM, Geraghty TJ, et al. Exercise and Sports Science Australia (ESSA) position statement on exercise and spinal cord injury. J Sci Med Sport. 2017;20(2):108–115.
8. Caspersen CJ, Powell KE, Christenson GM. Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. Public Health Rep. 1985;100(2):126–131.
9. Rauch A, Hinrichs T, Oberhauser C, Cieza A. Do people with spinal cord injury meet the WHO recommendations on physical activity? Int J Public Health. 2016;61(1):17–27.
10. Rocchi M, Routhier F, Latimer-Cheung AE, Ginis KAM, Noreau L, Sweet SN. Are adults with spinal cord injury meeting the spinal cord injury-specific physical activity guidelines? A look at a sample from a Canadian province. Spinal Cord. 2017;55(5):454–459.
11. Kressler J, Cowan RE, Bigford GE, Nash MS. Reducing cardiometabolic disease in Spinal Cord Injury. Phys Med Rehabil Clin N Am. 2014;25(3):573–604.
12. Powell KE, Paluch AE, Blair SN. Physical activity for health: What kind? how much? how intense? on top of what? Annu Rev Public Health. 2011;32:349–365.
13. De Groot S, Dallmeijer AJ, Post MWM, et al. Demographics of the Dutch multicenter prospective cohort study "Restoration of mobility in spinal cord injury rehabilitation." Spinal Cord. 2006;44(11):668–675.
14. Adriaansen JJE, Van Asbeck FWA, Lindeman E, et al. Secondary health conditions in persons with a spinal cord injury for at least 10 years: Design of a comprehensive long-term cross-sectional study. Disabil Rehabil. 2013;35(13):1104–1110.
15. Maynard FM, Bracken MB, Creasey G, Ditunno JF, et al. International standards for neurological and functional classification of spinal cord injury. Spinal Cord. 1997;35(5):266–274.
16. Van Koppenhagen CF, De Groot S, Post MWM, et al. Wheelchair exercise capacity in spinal cord injury up to five years after discharge from inpatient rehabilitation. J Rehabil Med. 2013;45(7):646–52.
17. Washburn RA, Zhu W, McAuley E, et al. The physical activity scale for individuals with physical disabilities: Development and evaluation. Arch Phys Med Rehabil. 2002;83(2):193–200.
18. Centraal Bureau voor de Statistiek. Standaard Onderwijsindeling 2017/2018; 2018.

19. Miller MR, Hankinson J, Brusasco V, et al. Standardisation of spirometry. Eur Respir J. 2005;26(2):319–338.

20. American College of Sports Medicine. ACSM's guidelines for exercise testing and prescription. 6th ed. Philadelphia (PA): Lippincott Williams & Wilkins; 2000.

21. de Groot S, van der Scheer JW, Bakkum AJT, et al. Wheelchair-specific fitness of persons with a long-term spinal cord injury: cross-sectional study on effects of time since injury and physical activity level. Disabil Rehabil. 2016;38(12):1180–1186.

22. Williams B, Mancia G, Spiering W, et al. ESC/ESH Guidelines for the management of arterial hypertension. J Hypertens. 2018;36(12):2284–2309.

23. Health Council of the Netherlands. Dutch physical activity guidelines 2017. The Hague; Health Council of the Netherlands; 2017.

24. Schilero GJ, Spungen AM, Bauman WA, et al. Pulmonary function and spinal cord injury. Respir Physiol Neurobiol. 2009;166(3):129–141.

25. Janssen TWJ, Van Oers CAJM, Veeger HEJ, et al. Relationship between physical strain during standardised ADL tasks and physical capacity in men with spinal cord injuries. Paraplegia. 1994;32(12):844–859.

26. Van Velzen JM, De Groot S, Post MWM, et al. Return to work after spinal cord injury: Is it related to wheelchair capacity at discharge from clinical rehabilitation? Am J Phys Med Rehabil. 2009;88(1):47–56.

27. Kouwijzer I, de Groot S, van Leeuwen CM, et al. Changes in Quality of Life During Training for the HandbikeBattle and Associations With Cardiorespiratory Fitness. Arch Phys Med Rehabil. 2020;101(6):1017–1024.

28. Fuchs FD, Whelton PK. High Blood Pressure and Cardiovascular Disease. Hypertension. 2020;75(2):285–292.

29. Van Den Berg-Emons RJ, L'Ortye AA, Buffart LM, et al. Validation of the physical activity scale for individuals with physical disabilities. Arch Phys Med Rehabil. 2011;92(6):923–928.

Supplementary appendix 1

Table 4a. Multiple regression analyses on respiratory function outcomes with inactive as reference.

Variables included in the model	FVC (L)			FEV1 (L)			FIV1 (L)		
	B (SE)	P	95% CI	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	3.88 (.36)	<.001	3.17, 4.59	3.43 (.27)	<.001	2.89, 3.97	3.16 (.33)	<.001	2.51, 3.81
MG guidelines vs. inactive	.73 (.19)	<.001	.37, 1.10	.45 (.14)	.002	.17, .73	.50 (.17)	.004	.16, .85
TW guidelines vs. inactive	.66 (.14)	<.001	.38, .94	.44 (.11)	<.001	.23, .66	.59 (.13)	<.001	.32, .84
Potential confounders									
Sex	.48 (.10)	<.001	.28, .67	.33 (.08)	<.001	.18, .48	.38 (.09)	<.001	.20, .56
Age	-.02 (.01)	.002	-.04, -.01	-.02 (.01)	<.001	-.03, -.01	-.01 (.01)	.045	-.03, .00
Lower educational level vs. middle	.20 (.17)	.263	-.15, .54	.14 (.13)	.299	-.12, .40	.08 (.16)	.607	-.24, .41
Higher educational level vs. middle	.10 (.15)	.504	-.19, .39	.10 (.11)	.395	-.13, .32	.04 (.14)	.785	-.23, .31
TSI	-.003 (.01)	.688	-.02, .01	-.002 (.01)	.691	-.01, .01	-.003 (.01)	.601	-.02, .01
Etiology SCI	-.07 (.20)	.716	-.48, .33	-.22 (.16)	.163	-.53, .09	-.11 (.18)	.565	-.48, .26
Lesion level	.38 (.09)	<.001	.20, .56	.29 (.07)	<.001	.15, .43	.35 (.08)	<.001	.18, .51
Lesion completeness	.57 (.16)	<.001	.26, .88	.46 (.12)	<.001	.22, .70	.46 (.15)	.002	.17, .75

	PEF (L/s)			PIF (L/s)		
	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	5.32 (.66)	<.001	4.01, 6.62	4.96 (.54)	<.001	3.89, 6.03
MG guidelines vs. inactive	.98 (.35)	.005	.30, 1.66	.15 (.29)	.605	-.41, .71
TW guidelines vs. inactive	1.12 (.27)	<.001	.59, 1.64	.87 (.22)	<.001	.45, 1.30
Potential confounders						
Sex	.61 (.19)	.001	.24, .97	.42 (.15)	.006	.12, .72
Age	-.02 (.01)	.082	-.05, .00	-.03 (.01)	.028	-.05, .00
Lower educational level vs. middle	.45 (.32)	.163	-.18, 1.09	.09 (.27)	.746	-.44, .61
Higher educational level vs. middle	.45 (.27)	.099	-.09, .99	.08 (.22)	.735	-.37, .52
TSI	.01 (.01)	.309	-.01, .04	.01 (.01)	.360	-.01, .03
Etiology SCI	-.39 (.38)	.305	-1.13, .36	-.29 (.31)	.352	-.90, .32
Lesion level	.71 (.17)	<.001	.38, 1.05	.53 (.14)	<.001	.25, .80
Lesion completeness	.75 (.29)	.012	.17, 1.33	.20 (.24)	.426	-.29, .68

Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

Table 4b. Multiple regression analyses on respiratory function outcomes with MG guidelines as reference.

Variables included in the model	FVC (L)			FEV1 (L)			FIV1 (L)		
	B (SE)	P	95% CI	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	4.62 (.36)	<.001	3.90, 5.33	3.88 (.27)	<.001	3.34, 4.43	3.66 (.34)	<.001	3.00, 4.32
Inactive vs. MG guidelines	-.73 (.19)	<.001	-1.10, -.37	-.45 (.14)	.002	-.73, -.17	-.50 (.17)	.004	-.85, -.16
TW guidelines vs. MG guidelines	-.07 (.18)	.688	-.43, .29	-.01 (.14)	.966	-.28, .27	.08 (.17)	.638	-.25, .41
Potential confounders									
Sex	.48 (.10)	<.001	.28, .67	.33 (.08)	<.001	.18, .48	.38 (.09)	<.001	.20, .56
Age	-.02 (.01)	.002	-.04, -.01	-.02 (.01)	<.001	-.03, -.01	-.01 (.01)	.045	-.03, .00
Lower educational level vs. middle	.20 (.17)	.263	-.15, .54	.14 (.13)	.299	-.12, .40	.08 (.16)	.607	-.24, .41
Higher educational level vs. middle	.10 (.15)	.504	-.19, .39	.10 (.11)	.395	-.13, .32	.04 (.14)	.785	-.23, .31
TSI	-.003 (.01)	.688	-.02, .01	-.002 (.01)	.691	-.01, .01	-.003 (.01)	.601	-.02, .01
Etiology SCI	-.07 (.20)	.716	-.48, .33	-.22 (.16)	.163	-.53, .09	-.11 (.18)	.565	-.48, .26
Lesion level	.38 (.09)	<.001	.20, .56	.29 (.07)	<.001	.15, .43	.35 (.08)	<.001	.18, .51
Lesion completeness	.57 (.16)	<.001	.26, .88	.46 (.12)	<.001	.22, .70	.46 (.15)	.002	.17, .75

	PEF (L/s)			PIF (L/s)		
	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	6.29 (.67)	<.001	4.97, 7.62	5.10 (.55)	<.001	4.02, 6.87
Inactive vs. MG guidelines	-.98 (.35)	.005	-1.66, -.30	-.15 (.28)	.605	-.71, .41
TW guidelines vs. MG guidelines	.14 (.34)	.682	-.53, .80	.73 (.28)	.009	.18, 1.27
Potential confounders						
Sex	.61 (.19)	.001	.24, .97	.42 (.15)	.006	.12, .72
Age	-.02 (.01)	.082	-.05, .00	-.03 (.01)	.028	-.05, .00
Lower educational level vs. middle	.45 (.32)	.163	-.18, 1.09	.10 (.26)	.701	-.44, .61
Higher educational level vs. middle	.45 (.27)	.099	-.09, .99	.12 (.22)	.600	-.37, .52
TSI	.01 (.01)	.309	-.01, .04	.01 (.01)	.360	-.01, .03
Etiology SCI	-.40 (.38)	.305	-1.13, .36	-.37 (.30)	.227	-.90, .32
Lesion level	.71 (.17)	<.001	.38, 1.05	.53 (.14)	<.001	.25, .80
Lesion completeness	.75 (.29)	.012	.17, 1.33	.20 (.24)	.426	-.29, .68

Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

Table 5a. Multiple regression analyses on exercise capacity outcomes with inactive as reference.

Variables included in the model	VO2peak (L/min)			Relative VO2peak (ml/kg/min)		
	B (SE)	**P**	**95% CI**	**B (SE)**	**P**	**95% CI**
Constant	1.13 (.21)	<.001	.71, 1.55	16.26 (2.71)	<.001	10.90, 21.61
MG guidelines vs. inactive	.10 (.11)	.389	-.13, .32	2.46 (1.45)	.091	-.40, 5.31
TW guidelines vs. inactive	.31 (.09)	.001	.13, .50	4.49 (1.20)	<.001	2.12, 6.85
Potential confounders						
Sex	.14 (.05)	.005	.04, .24	1.03 (.63)	.105	-.22, 2.27
Age	-.01 (.01)	.104	-.02, .00	-.13 (.06)	.033	-.25, -.01
Lower educational level vs. middle	.11 (.11)	.338	-.11, .32	1.61 (1.40)	.250	-1.14, 4.37
Higher educational level vs. middle	.10 (.09)	.260	-.07, .27	.56 (1.10)	.611	-1.61, 2.74
TSI	<.001 (.01)	.966	-.01, .01	.004 (.06)	.940	-.11, .12
Etiology SCI	-.04 (.13)	.767	-.29, .21	-.21 (1.64)	.900	-3.43, 3.02
Lesion level	.24 (.05)	<.001	.14, .33	2.61 (.60)	<.001	1.42, 3.80
Lesion completeness	.06 (.10)	.551	-.13, .25	-.34 (1.25)	.788	-2.81, 2.14
	POpeak (W)			**Relative POpeak (W/kg)**		
	B (SE)	**P**	**95% CI**	**B (SE)**	**P**	**95% CI**
Constant	40.49 (10.01)	<.001	20.55, 60.42	.58 (.12)	<.001	.37, .83
MG guidelines vs. inactive	7.93 (5.77)	.171	-3.46, 19.32	.14 (.07)	.047	.00, .28
TW guidelines vs. inactive	18.78 (4.59)	<.001	9.72, 27.85	.25 (.06)	<.001	.14, .36
Potential confounders						
Sex	5.24 (2.32)	.025	.67, 9.83	.04 (.03)	.158	-.02, .10
Age	-.47 (.22)	.033	-.89, -.04	-.01 (.003)	.010	-.01, -.00
Lower educational level vs. middle	2.94 (5.26)	.578	-7.46, 13.33	.03 (.06)	.623	-.10, .16
Higher educational level vs. middle	7.07 (4.17)	.092	-1.18, 15.31	.06 (.05)	.230	-.04, .16
TSI	.18 (.22)	.409	-.25, .60	.002 (.003)	.345	-.00, .01
Etiology SCI	6.14 (6.29)	.331	-6.28, 18.56	.12 (.08)	.132	-.04, .27
Lesion level	10.14 (2.22)	<.001	5.76, 14.53	.12 (.03)	<.001	.06, .17
Lesion completeness	-6.13 (4.89)	.207	-15.85, 3.46	-.11 (.06)	.069	-.23, .01

Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

Table 5b. Multiple regression analyses on exercise capacity outcomes with MG guidelines as reference.

Variables included in the model	VO2peak (L/min)			Relative VO2peak (ml/kg/min)		
	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	1.23 (.21)	<.001	.82, 1.63	18.71 (2.64)	<.001	13.50, 23.93
Inactive vs. MG guidelines	-.10 (.11)	.389	-.32, 1.25	-.2.46 (1.44)	.091	-5.31, .40
TW guidelines vs. MG guidelines	.21 (.09)	.022	.03, .40	2.03 (1.19)	.089	-.31, 4.37
Potential confounders						
Sex	.14 (.05)	.005	.04, .24	1.03 (.63)	.105	-.22, 2.27
Age	-.01 (.01)	.104	-.02, .00	-.13 (.06)	.033	-.25, -.01
Lower educational level vs. middle	.11 (.11)	.338	-.11, .32	1.61 (1.40)	.250	-1.14, 4.37
Higher educational level vs. middle	.10 (.09)	.260	-.07, .27	.56 (1.10)	.611	-1.61, 2.74
TSI	<.001 (.01)	.966	-.01, .01	.004 (.06)	.940	-.11, .12
Etiology SCI	-.04 (.13)	.767	-.29, .21	-.21 (1.64)	.900	-3.43, 3.02
Lesion level	.24 (.05)	<.001	.14, .33	2.61 (.60)	<.001	1.42, 3.80
Lesion completeness	.06 (.10)	.551	-.13, .25	-.34 (1.25)	.788	-2.81, 2.14
	POpeak (W)			**Relative POpeak (W/kg)**		
	B (SE)	**P**	**95% CI**	**B (SE)**	**P**	**95% CI**
Constant	48.42 (10.10)	<.001	28.48, 68.36	.72 (.12)	<.001	.48, .97
Inactive vs. MG guidelines	-7.93 (5.76)	.171	-19.32, 3.46	-.14 (.07)	.047	-.28, -.00
TW guidelines vs. MG guidelines	10.85 (4.82)	.026	1.34, 20.36	.11 (.06)	.068	-.01, .22
Potential confounders						
Sex	5.25 (2.32)	.025	.67, 9.83	.04 (.03)	.158	-.02, .10
Age	-.47 (.22)	.033	-.89, -.04	-.01 (.003)	.010	-.01, -.00
Lower educational level vs. middle	2.94 (5.26)	.578	-7.46, 13.33	.03 (.06)	.623	-.10, .16
Higher educational level vs. middle	7.07 (4.17)	.092	-1.18, 15.31	.06 (.05)	.230	-.04, .16
TSI	.18 (.22)	.409	-.25, .60	.002 (.003)	.345	-.00, .01
Etiology SCI	6.14 (6.29)	.331	-6.28, 18.56	.12 (.08)	.132	-.04, .27
Lesion level	10.14 (2.22)	<.001	5.76, 14.53	.12 (.03)	<.001	.06, .17
Lesion completeness	-6.19 (4.89)	.207	-15.85, 3.46	-.11 (.06)	.069	-.23, .01

Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

Table 6a. Multiple regression analyses on health outcomes with inactive as reference.

Variables included in the model	WC (cm)			BMI			SBP (mmHg)		
	B (SE)	P	95% CI	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	88.02 (7.87)	<.001	71.49, 103.55	21.39 (1.62)	<.001	18.20, 24.56	82.14 (7.43)	<.001	67.53, 96.75
MG guidelines vs. inactive	-3.41 (3.07)	.268	-9.46, 2.65	-1.79 (.86)	.039	-3.48, -.09	4.75 (3.80)	.213	-2.73, 12.22
TW guidelines vs. inactive	-6.36 (2.34)	.007	-10.97, -1.74	-.92 (.66)	.162	-2.21, .37	8.47 (2.96)	.005	2.65, 14.30
Potential confounders									
Sex	9.87 (2.51)	<.001	4.93, 14.82	.42 (.37)	.255	-.30, 1.14	1.54 (3.00)	.608	-4.36, 7.44
Age	.09 (.23)	.688	-.36, .55	.10 (.03)	.003	.04, .17	.53 (.15)	.001	.23, .83
Lower educational level vs. middle	-2.30 (3.14)	.465	-8.50, 3.90	.15 (.80)	.851	-1.43, 1.73	.73 (3.54)	.836	-6.23, 7.69
Higher educational level vs. middle	-1.47 (2.65)	.580	-6.69, 3.76	.47 (.68)	.492	-.87, 1.81	1.85 (3.03)	.541	-4.11, 7.81
TSI	.13 (.22)	.554	-.31, .57	-.03 (.03)	.345	-.09, .03	.27 (.14)	.054	-.01, .55
Etiology SCI	4.72 (3.75)	.209	-2.67, 12.11	-.37 (.94)	.695	-2.22, 1.48	4.58 (4.11)	.266	-3.51, 12.68
Lesion level	-.56 (1.31)	.669	-3.15, 2.03	.15 (.42)	.717	-.68, .98	7.05 (1.85)	<.001	3.40, 10.69
Lesion completeness	.003 (2.81)	.999	-5.54, 5.55	.35 (.73)	.637	-1.10, 1.79	1.20 (3.23)	.701	-5.16, 7.57

	DBP (mmHg)			MAP (mmHg)			Hypertension			
	B (SE)	P	95% CI	B (SE)	P	95% CI	B (SE)	P	OR	95% CI
Constant	56.73 (4.46)	<.001	47.95, 65.51	65.20 (5.21)	<.001	54.94, 75.46	-3.69 (.82)	<.001	.03	-5.30, -2.08
MG guidelines vs. inactive	.48 (2.28)	.834	-4.01, 4.97	1.90 (2.67)	.476	-3.35, 7.15	.35 (.40)	.381	1.42	-.43, 1.14
TW guidelines vs. inactive	2.74 (1.78)	.125	-.77, 6.24	4.65 (2.08)	.026	.56, 8.74	.29 (.32)	.364	1.33	-.33, .91
Potential confounders										
Sex	-.53 (1.80)	.767	-4.08, 3.01	.16 (2.10)	.941	-3.98, 4.30	.13 (.32)	.675	1.14	-.49, .75
Age	.27 (.09)	.002	.11, .47	.37 (.11)	.001	.16, .58	.03 (.21)	<.053	1.03	.00, .07
Lower educational level vs. middle	.88 (2.13)	.678	-3.30, 5.06	.83 (2.48)	.738	-4.05, 5.72	-.44 (.38)	.244	.64	-1.19, .30
Higher educational level vs. middle	.99 (1.82)	.587	-2.59, 4.57	1.28 (2.13)	.548	-2.91, 5.46	.05 (.31)	.879	.95	-.66, .57
TSI	.06 (.08)	.517	-.11, .22	.13 (.10)	.198	-.07, .32	.03 (.01)	.021	1.03	.01, .06
Etiology SCI	1.87 (2.47)	.451	-3.00, 6.73	2.77 (2.89)	.338	-2.91, 8.45	.01 (.42)	.990	1.01	-.81, .82
Lesion level	4.79 (1.11)	<.001	2.60, 6.98	5.54 (1.30)	<.001	2.98, 8.10	.76 (.28)	.007	2.14	.21, 1.31
Lesion completeness	.92 (1.94)	.637	-2.91, 4.74	1.01 (2.27)	.656	-3.46, 5.48	-.21 (.33)	.533	1.23	-.44, .85

Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

Table 6b. Multiple regression analyses on health outcomes with MG guidelines as reference.

Variables included in the model	WC (cm)			BMI			SBP (mmHg)		
	B (SE)	P	95% CI	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	84.61 (8.21)	<.001	68.42, 100.80	19.61 (1.64)	<.001	16.38, 22.83	86.87 (7.45)	<.001	72.23, 101.54
Inactive vs. MG guidelines	3.41 (3.07)	.268	-2.65, 9.46	1.79 (.86)	.039	.09, -3.48	-4.75 (3.80)	.213	-12.22, 2.73
TW guidelines vs. MG guidelines	-2.95 (3.00)	.327	-8.87, 2.91	.87 (.84)	.301	-.78, 2.52	3.73 (3.70)	.315	-3.56, 11.02
Potential confounders									
Sex	9.87 (2.51)	<.001	4.93, 14.82	.42 (.37)	.255	-.30, 1.14	1.54 (3.00)	.608	-4.36, 7.44
Age	.09 (.23)	.688	-.36, .55	.10 (.03)	.003	.04, .17	.53 (.15)	.001	.23, .83
Lower educational level vs. middle	-2.30 (3.14)	.465	-8.50, 3.90	.15 (.80)	.851	-1.43, 1.73	.73 (3.54)	.836	-6.23, 7.69
Higher educational level vs. middle	-1.47 (2.65)	.580	-6.69, 3.76	.47 (.68)	.492	-.87, 1.81	1.85 (3.03)	.541	-4.11, 7.81
TSI	.13 (.22)	.554	-.31, .57	-.03 (.03)	.345	-.09, .03	.27 (.14)	.054	-.01, .55
Etiology SCI	4.72 (3.75)	.209	-2.67, 12.11	-.37 (.94)	.695	-2.22, 1.48	4.58 (4.11)	.266	-3.51, 12.68
Lesion level	-.56 (1.31)	.669	-3.15, 2.03	.15 (.42)	.717	-.68, .98	7.05 (1.85)	<.001	3.40, 10.69
Lesion completeness	.003 (2.81)	.999	-5.54, 5.55	.35 (.73)	.637	-1.10, 1.79	1.20 (3.23)	.710	-5.16, 7.57

	DBP (mmHg)			MAP (mmHg)			Hypertension			
	B (SE)	P	95% CI	B (SE)	P	95% CI	B (SE)	P	OR	95% CI
Constant	57.21 (4.47)	<.001	48.40, 66.01	67.10 (5.23)	<.001	56.81, 77.39	-3.34 (.82)	<.001	.04	-4.95, -1.73
Inactive vs. MG guidelines	-.48 (2.28)	.834	-4.97, 4.01	-1.90 (2.67)	.476	-7.15, 3.35	-.35 (.40)	.381	.70	-1.14, .43
TW guidelines vs. MG guidelines	2.26 (2.23)	.312	-2.12, 6.67	2.75 (2.60)	.292	-2.37, 7.87	-.06 (.39)	.868	.94	-.82, .69
Potential confounders										
Sex	-.53 (1.80)	.767	-4.08, 3.01	.16 (2.10)	.941	-3.98, 4.30	.13 (.32)	.675	1.14	-.49, .75
Age	.29 (.09)	.002	.11, .47	.37 (.11)	.001	.16, .58	.03 (.21)	<.053	1.03	.00, .07
Lower educational level vs. middle	.88 (2.13)	.678	-3.30, 5.06	.83 (2.48)	.738	-4.05, 5.72	-.44 (.38)	.244	.64	-1.19, .30
Higher educational level vs. middle	.99 (1.82)	.587	-2.59, 4.57	1.28 (2.13)	.548	-2.91, 5.46	.05 (.31)	.879	.95	-.66, .57
TSI	.01 (.08)	.517	-.11, .22	.13 (.10)	.198	-.07, .32	.03 (.01)	.021	1.03	.01, .06
Etiology SCI	1.87 (2.47)	.451	-3.00, 6.73	2.77 (2.89)	.338	-2.91, 8.45	.01 (.42)	.990	1.01	-.81, .82
Lesion level	4.79 (1.11)	<.001	2.60, 6.98	5.54 (1.30)	<.001	2.98, 8.10	.76 (.28)	.007	2.14	.21, 1.31
Lesion completeness	.92 (1.94)	.637	-2.91, 4.74	1.01 (2.27)	.656	-3.46, 5.48	-.21 (.33)	.533	1.23	-.44, .85

Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

2

Table 7a. Multiple regression analyses on lipid profile with inactive as reference.

Variables included in the model	TC (mmol/L)			HDL (mmol/L)			TC/HDL ratio		
	B (SE)	**P**	**95% CI**	**B (SE)**	**P**	**95% CI**	**B (SE)**	**P**	**95% CI**
Constant	4.03 (.36)	<.001	3.32, 4.75	.98 (.12)	<.001	.75, 1.21	4.45 (.50)	<.001	3.48, 5.43
MG guidelines vs. inactive	.26 (.19)	.168	-.11, .63	.08 (.06)	.199	-.04, .20	-.09 (.26)	.726	-.60, .42
TW guidelines vs. inactive	.03 (.14)	.839	-.25, .31	.03 (.05)	.588	-.07, .12	-.02 (.20)	.937	-.37, .40
Potential confounders									
Sex	-.16 (.14)	.253	-.44, .12	-.21 (.05)	<.001	-.30, -.12	.54 (.20)	.006	.15, .92
Age	.02 (.01)	.043	.00, .03	.01 (.002)	.015	.00, .01	-.01 (.01)	.579	-.03, .01
Lower educational level vs. middle	.05 (.17)	.770	-.29, .39	-.06 (.06)	.347	-.16, .06	.18 (.24)	.437	-.28, .65
Higher educational level vs. middle	.16 (.15)	.301	-.14, .45	.10 (.05)	.039	.01, .19	-.37 (.21)	.077	-.78, .04
TSI	-.001 (.01)	.835	-.02, .01	-.001 (.002)	.805	-.01, .00	-.001 (.01)	.904	-.02, .02
Etiology SCI	-.10 (.20)	.601	-.49, .28	.05 (.06)	.440	-.08, .17	-.32 (.27)	.237	-.85, .21
Lesion level	.09 (.09)	.321	-.08, .26	.02 (.03)	.451	-.03, .08	-.02 (.12)	.861	-.25, .21
Lesion completeness	.30 (.16)	.062	-.02, .61	.07 (.05)	.155	-.03, .17	-.03 (.22)	.908	-.45, .40

	LDL (mmol/L)			TG (mmol/L)		
	B (SE)	**P**	**95% CI**	**B (SE)**	**P**	**95% CI**
Constant	2.49 (.31)	<.001	1.87, 3.11	1.36 (.42)	.001	.53, 2.19
MG guidelines vs. inactive	.13 (.16)	.420	-.19, .45	.07 (.22)	.754	-.36, .50
TW guidelines vs. inactive	-.09 (.13)	.473	-.34, .16	.20 (.17)	.221	-.12, .53
Potential confounders						
Sex	-.05 (.12)	.675	-.30, .19	.34 (.16)	.039	.02, .67
Age	.01 (.01)	.182	-.00, .02	.003 (.01)	.731	-.01, .02
Lower educational level vs. middle	.11 (.15)	.480	-.19,. 41	-.01 (.20)	.963	-.41, .39
Higher educational level vs. middle	.22 (.13)	.090	-.04, .48	-.41 (.17)	.019	-.75, -.07
TSI	-.002 (.01)	.792	-.01, .01	<.001 (.01)	.960	-.02, .02
Etiology SCI	-.15 (.18)	.403	-.49, .20	.26 (.23)	.272	-.20, .71
Lesion level	.09 (.08)	.211	-.05, .24	-.07 (.10)	.471	-.27, .13
Lesion completeness	.75 (.29)	.012	.00, .55	.20 (.24)	.426	-.70, .03

Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

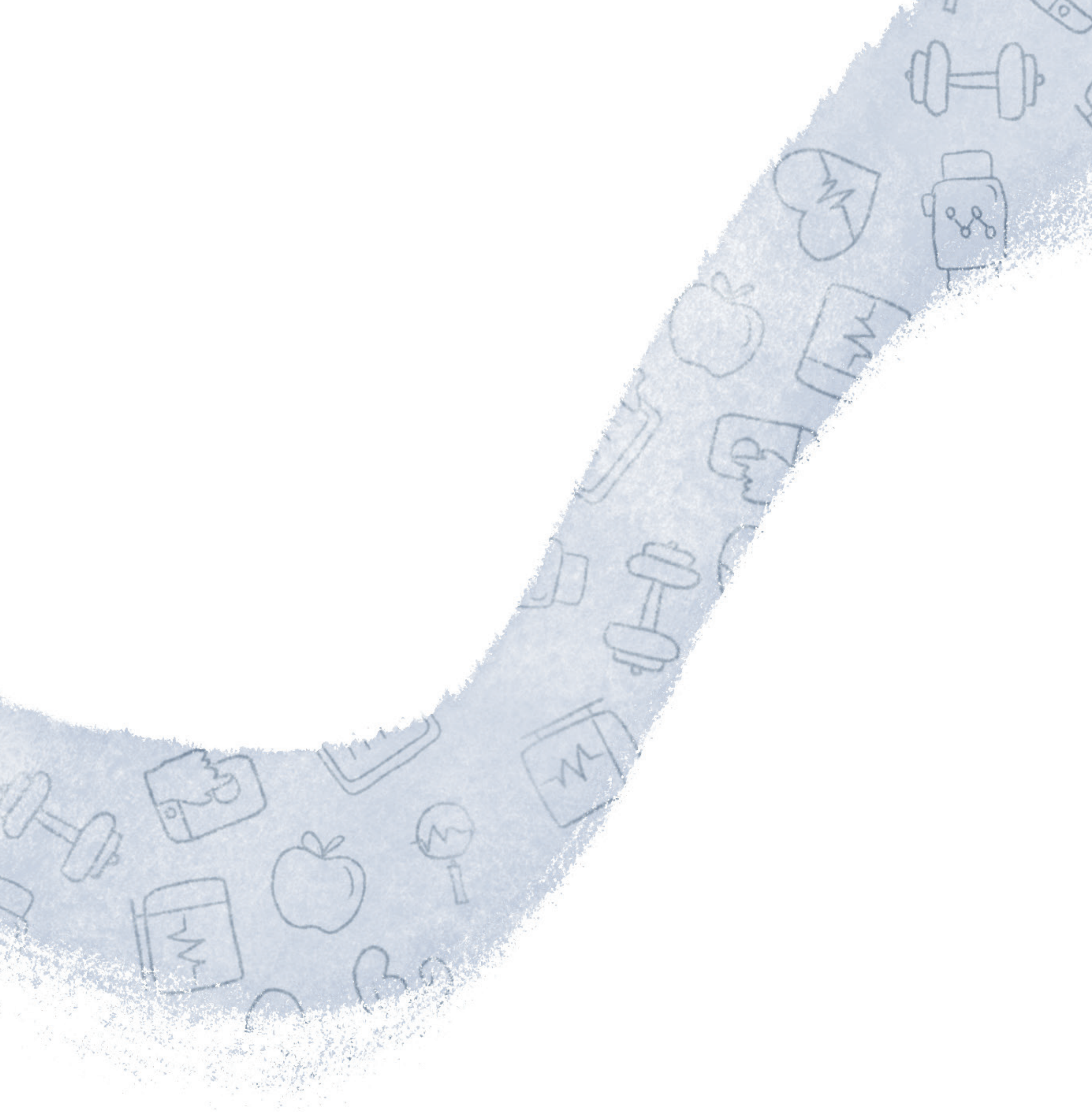
Table 7b. Multiple regression analyses on lipid profile with MG guidelines as reference.

Variables included in the model	TC (mmol/L)			HDL (mmol/L)			TC/HDL ratio		
	B (SE)	P	95% CI	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	4.29 (.37)	<.001	3.57, 5.02	1.06 (.12)	<.001	.82, 1.29	4.36 (.51)	<.001	3.37, 5.36
Inactive vs. MG guidelines	-.26 (.19)	.168	-.63, .11	-.08 (.06)	.199	-..20, .04	.09 (.26)	.726	-.42, .60
TW guidelines vs. MG guidelines	-.23 (.19)	.216	-.60, .14	-.05 (.06)	.377	-.17, .06	.11 (.25)	.678	-.40, .61
Potential confounders									
Sex	-.16 (.14)	.253	-.44, .12	-.21 (.05)	<.001	-.30, -.12	.54 (.20)	.006	.15, .92
Age	.02 (.01)	.043	.00, .03	.01 (.002)	.015	.00, .01	-.01 (.01)	.579	-.03, .01
Lower educational level vs. middle	.05 (.17)	.770	-.29, .39	-.06 (.06)	.347	-.16, .06	.18 (.24)	.437	-.28, .65
Higher educational level vs. middle	.16 (.15)	.301	-.14, .45	.10 (.05)	.039	.01, .19	-.37 (.21)	.077	-.78, .04
TSI	-.001 (.01)	.835	-.02, .01	-.001 (.002)	.805	-.01, .00	-.001 (.01)	.904	-.02, .02
Etiology SCI	-.10 (.20)	.601	-.49, .28	.05 (.06)	.440	-.08, .17	-.32 (.27)	.237	-.85, .21
Lesion level	.09 (.09)	.321	-.08, .26	.02 (.03)	.451	-.03, .08	-.02 (.12)	.861	-.25, .21
Lesion completeness	.30 (.16)	.062	-.02, .61	.07 (.05)	.155	-.03, .17	-.03 (.22)	.908	-.45, .40

	LDL (mmol/L)			TG (mmol/L)		
	B (SE)	P	95% CI	B (SE)	P	95% CI
Constant	2.62 (.32)	<.001	1.99, 3.25	1.43 (.43)	.001	.59, 2.27
Inactive vs. MG guidelines	-.13 (.16)	.420	-.45, .19	-.07 (.22)	.754	-.50, .36
TW guidelines vs. MG guidelines	-.22 (.16)	.171	-.53, .10	.14 (.22)	.532	-.29, .56
Potential confounders						
Sex	-.05 (.12)	.675	-.30, .19	.34 (.16)	.039	.02, .67
Age	.01 (.01)	.182	-.00, .02	.003 (.01)	.731	-.01, .02
Lower educational level vs. middle	.11 (.15)	.480	-.19,. 41	-.01 (.20)	.963	-.41, .39
Higher educational level vs. middle	.22 (.13)	.090	-.04, .48	-.41 (.17)	.019	-.75, -.07
TSI	-.002 (.01)	.792	-.01, .01	<.001 (.01)	.960	-.02, .02
Etiology SCI	-.15 (.18)	.403	-.49, .20	.26 (.23)	.272	-.20, .71
Lesion level	.09 (.08)	.211	-.05, .24	-.07 (.10)	.471	-.27, .13
Lesion completeness	.75 (.29)	.012	.00, .55	.20 (.24)	.426	-.70, .03

Sex was coded as female = 0 and male = 1; lesion level as tetraplegia = 0 and paraplegia = 1; lesion completeness as complete = 0 and incomplete = 1; etiology as traumatic = 0 and non-traumatic = 1 and middle educational level was used as reference variable.

2



Chapter 3

Accuracy of Heart Rate Measurement by the Fitbit Charge 2 During Wheelchair Activities in People With Spinal Cord Injury: Instrument Validation Study

Published as: Hoevenaars D, Yocarini IE, Paraschiakos S, Holla JFM, de Groot S, Kraaij W, Janssen TWJ. Accuracy of Heart Rate Measurement by the Fitbit Charge 2 During Wheelchair Activities in People With Spinal Cord Injury: Instrument Validation Study. JMIR Rehabilitation Assistive Technologies. 2022 Jan 19;9(1):e27637.

Abstract

Background: Heart rate (HR) is an important and commonly measured physiological parameter in wearables. HR is often measured at the wrist with the photoplethysmography (PPG) technique, which determines HR based on blood volume changes, and is therefore influenced by blood pressure. In individuals with spinal cord injury (SCI), blood pressure control is often altered and could therefore influence HR accuracy measured by the PPG technique.

Objective: The objective of this study is to investigate the HR accuracy measured with the PPG technique with a Fitbit Charge 2 (Fitbit Inc) in wheelchair users with SCI, how the activity intensity affects the HR accuracy, and whether this HR accuracy is affected by lesion level.

Methods: The HR of participants with (38/48, 79%) and without (10/48, 21%) SCI was measured during 11 wheelchair activities and a 30-minute strength exercise block. In addition, a 5-minute seated rest period was measured in people with SCI. HR was measured with a Fitbit Charge 2, which was compared with the HR measured by a Polar H7 HR monitor used as a reference device. Participants were grouped into 4 groups—the no SCI group and based on lesion level into the <T5 (midthoracic and lower) group, T5-T1 (high-thoracic) group, and >T1 (cervical) group. Mean absolute percentage error (MAPE) and concordance correlation coefficient were determined for each group for each activity type, that is, rest, wheelchair activities, and strength exercise.

Results: With an overall $MAPE_{all\ lesions}$ of 12.99%, the accuracy fell below the standard acceptable MAPE of –10% to +10% with a moderate agreement (concordance correlation coefficient=0.577). The HR accuracy of Fitbit Charge 2 seems to be reduced in those with cervical lesion level in all activities ($MAPE_{no\ SCI}$=8.09%; $MAPE_{<T5}$=11.16%; $MAPE_{T1–T5}$=10.5%; and $MAPE_{>T1}$=20.43%). The accuracy of the Fitbit Charge 2 decreased with increasing intensity in all lesions ($MAPE_{rest}$=6.5%, $MAPE_{activity}$=12.97%, and $MAPE_{strength}$=14.2%).

Conclusions: HR measured with the PPG technique showed lower accuracy in people with SCI than in those without SCI. The accuracy was just above the acceptable level in people with paraplegia, whereas in people with tetraplegia, a worse accuracy was found. The accuracy seemed to worsen with increasing intensities. Therefore, high-intensity HR data, especially in people with cervical lesions, should be used with caution.

Keywords: Fitbit Charge 2; heart rate; accuracy; photoplethysmography; spinal cord injury

Introduction

Background

Spinal cord injury (SCI) is a result of a partial or complete disruption of the neuropathways in the spinal cord, causing loss of motor and sensory function and a disturbed autonomic nervous system (ANS). Wheelchair users with SCI have one of the lowest daily activity levels compared to other groups with chronic physical conditions [1], negatively affecting their daily activity energy expenditure. In addition, their resting energy expenditure is often decreased because of multiple factors, with a reduced fat-free mass as a major contributor [2–5]. Together with the reduced activity energy expenditure, this leads to a lower total daily energy expenditure. As a consequence, approximately 68% of the people with SCI are overweight or obese, associated with increased risks of cardiovascular disease and mortality [6,7]. Therefore, maintaining or achieving an active lifestyle is even more crucial in people with SCI than in the able-bodied population. There are several tools that can help to stimulate or maintain an active lifestyle. Currently, activity trackers are a popular way to get insight on and monitor one's personal activity level. Activity trackers include many features, such as estimations of activity levels, exercise intensity or daily energy expenditure, often based on recorded movement via accelerometry and heart rate (HR).

HR is one of the most important and often used physiological parameters, as it is directly related to oxygen consumption and energy expenditure. The delivery of oxygen-rich blood required in the circulation system is controlled by the ANS by modulating both the HR and stroke volume [8,9]. For this reason, HR is used to monitor exercise intensity or as a derivative to estimate, for example, maximal oxygen uptake (VO2max), or energy expenditure [10]. Over the last 4 decades, HR during exercise has mainly been measured using HR monitors that make use of a chest belt, transmitter, and receiver. Owing to the rapid development of sensor technology in recent decades, it is now possible to record and track HR in an even less invasive and easier way. One of the most popular and commonly used methods to determine HR in daily life is photoplethysmography (PPG), a simple and low-cost technique that can be integrated in a wrist-worn activity tracker [11,12].

PPG is a technique in which blood volume changes are detected in the microvascular bed of tissue by infrared light reflected from the tissue, such as the ear lobe, finger, or wrist [11]. The change in blood volume after a heartbeat is proportional to the reflected light, allowing pulse wave detection in the wrist, which can be used as a derivative to determine HR [13]. HR recording with this technique, however, is more susceptible to motion artifacts caused by hand-arm movements and blood flow dynamics and can, therefore, lead to a lower accuracy

[14,15]. Studies have shown acceptable validity and accuracy (<10%) in HR recordings during sleep or across a 24-hour period in a free-living environment in able-bodied individuals with a mean absolute percentage error (MAPE) of <10% [16,17]. However, when tested during activities of higher intensities or dynamic situations, the accuracy dropped (MAPE>10%) [18–20]. Owing to the developments in HR recording with activity trackers, they are being included in clinical settings for medical purposes, such as mobile health monitoring, noninvasive medical surveillance, or even detecting first signs of health issues [21–23]. As information gathered by activity trackers is more often used for clinical and health purposes, the importance of accurate data is growing. However, as measurement techniques rely on physiological properties and responses, measurement outcomes can differ if physiological responses are altered, for instance, because of medical conditions. Therefore, it is important to investigate the accuracy of HR measurement within different populations, such as in people with SCI, as their physiological responses can be severely altered [24].

Objectives

The accuracy of HR determined by PPG depends on blood pressure changes which is, among other things, influenced by HR variability [25]. Both, the blood pressure of the upper limbs and HR are regulated by the ANS, of which the sympathetic outflow occurs between the first thoracic (T1) spinal cord segment and the fifth thoracic (T5) spinal segment. After an SCI, neural signal transmission is partially or fully lost at and below the lesion level. In case of an SCI at or above the T5 spinal cord segment, neural signaling and, therefore, the balance between the parasympathetic and sympathetic systems are often altered. Sympathetic hypoactivity usually occurs, resulting in possible low HR, low resting blood pressure, disturbed vascular regulation, and altered responses in these systems during rest or during physical activities [24]. Owing to the changes in HR response and blood pressure control, the accuracy of HR determined by PPG could be affected when a lesion occurs above T5. Because of possible impaired or altered vascular regulation, artifact-reducing algorithms may not apply and might subsequently compromise HR accuracy. The ANS is even more affected in cervical lesions, as the imbalance between the parasympathetic and sympathetic systems increases with lesion level [26]. Therefore, the aim of this study is to evaluate whether Fitbit Charge 2 can accurately record HR in wheelchair users with SCIs and to investigate how lesion level affects accuracy. In addition, the effect of intensity on accuracy is determined during wheelchair activities and strength exercise, as a higher intensity is expected during strength exercise compared with wheelchair activities and during wheelchair activities compared with rest. It is hypothesized that the HR accuracy of the Fitbit Charge 2 is lower in people with lesions at or above T5 because of the possible affected ANS, compared with people with lesions below T5 or without SCI. A further reduction in accuracy is expected in people with a cervical lesion compared with those with a lower lesion level or without SCI, because of an enlarged imbalance between the parasympathetic and sympathetic systems. Furthermore, the accuracy is expected to decrease with increasing intensities.

Methods

Data on body composition and energy expenditure in people with SCI were collected in a larger cross-sectional study. All participants were invited for a one-time visit to the Amsterdam Nutritional Assessment Center laboratory of the Amsterdam University of Applied Sciences. HR of the participants was recorded during rest, wheelchair activities, and a 30-minute strength exercise block with both the Fitbit Charge 2 and Polar H7 HR monitor. All participants provided signed informed consent before participating. The study was approved by the medical ethical committee of Slotervaart Ziekenhuis—Reade (METc nr. P1805).

Participants

Overall, 48 participants were recruited to participate in this study, 38 (79%) with SCI and 10 (21%) without SCI. Recruitment took place through advertisements via the Dutch SCI patient association, social media, rehabilitation center Reade in Amsterdam, and the social network of the involved researchers. Participants were included if the following inclusion criteria were met: age between 18 and 75 years; chronic SCI (time since injury >1 year), not ventilator-dependent; and wheelchair-dependent for longer distances. Exclusion criteria were as follows: presence of a pacemaker, severe edema, progressive illness, pressure ulcers, metabolic diseases, severe comorbidities, psychiatric disorders, pregnancy, and insufficient understanding of the Dutch language to understand the study. Participants without SCI were selected based on the same inclusion and exclusion criteria, except for the SCI-related criteria. Personal and lesion characteristics were obtained through a questionnaire and interview. A conservative sample size target was chosen and set on ≥40 samples of each device for each group for each activity based on the method comparison guideline [27].

The participants were divided into 4 groups—the without SCI group and based on their lesion level they were divided into the cervical (>T1), high-thoracic (T1-T5), and midthoracic and lower (<T5) groups, to test the influence of lesion level on PPG accuracy. Heart and upper-body blood vessels are sympathetically innervated from segments T1-T5 and interact with the parasympathetic system to provide a balanced regulation of the cardiovascular system. In people with an SCI at T5 and above, sympathetic innervation is likely to be affected to a certain extent, which causes altered HR response and blood pressure regulation, possibly affecting PPG recordings compared with lower lesions. In addition, the lesion groups T5 and above were

divided into the following lesion subgroups: lesion above T1 and lesion between T1-T5, with a larger imbalance in the ANS expected in the first group and thus a more severe cardiovascular dysfunction [28]. In people with an SCI above T1, arm function might be impaired, as well as a more severed impaired sympathetic innervation of the heart and upper-body vessels compared to lower lesions, which could lead to a lower HR accuracy in those with a cervical lesion [29].

Materials

Fitbit Charge 2

The Fitbit Charge 2 (2017 version, Firmware version 22.55.2, Fitbit Inc) is a commercially available activity tracker with multiple sensors, such as a 3-axis accelerometer, an altimeter, and a PPG sensor to record HR. In the Fitbit Charge 2 PurePulse, HR technology is used as an investigational device, which constantly reads the changes in the blood volume at the wrist. An algorithm converts these data into continuous HR data. The smartwatch was tightly positioned according to instructions of Fitbit on the wrist of participants on which normally a watch would be worn, usually the nondominant side. Intraday data collection was requested and approved by Fitbit for research purposes, allowing us to obtain the data on the highest possible sampling rate for the time period in which all activities were performed through an application programing interface. Output frequency of the HR data varied between 0.2 Hz and 0.06 Hz. Data collected by the Fitbit were transferred through Bluetooth Low Energy to the Fitbit App and downloaded.

Polar H7 HR monitor

The Polar H7 chest strap HR monitor (Bluetooth Low Energy version, Polar Electro) was used as a reference device to measure HR; it is an accurate (intraclass correlation coefficient=0.98) alternative for a 3-lead electrocardiography (ECG), which is considered as the gold standard for measuring HR [30]. The strap was moistened to improve conduction between the skin and the sensor before it was secured tightly around the chest. HR recording was connected with a Cortex Metamax 3B (Cortex Biophysik GmbH) portable indirect calorimetry system, used in the larger study, which collects data at each full breathing cycle. Therefore, the output frequency of the Polar H7 HR data was determined by the breathing frequency of the participants during the protocol. The HR output given after each breathing cycle was the average HR measured over the entire breathing cycle.

Measurement protocol

After ensuring that all sensors were positioned correctly, the measurement protocol started with a 5-minute seated rest, followed by wheelchair activities, consisting of eleven different wheelchair tasks executed for 1 minute, namely: (1) wheelchair propulsion on a low-resistance surface on a slow, (2) normal, and (3) high speed; (4) handcycling on an armcrank ergometer; (5) rummaging in a bag while being pushed; (6) setting the table; (7) doing dishes; (8) typing on a laptop; (9) maneuvering the wheelchair; (10) wheelchair basketball; and (11) transfer from wheelchair to chair and back. No 5-minute seated rest data were available for the participants without SCI, as this was added to the measurement protocol after finishing the measurements of the participants without SCI. All tasks were performed for 1 minute, as this represents real-life situations better compared with longer steady-state situations. All tasks were timed, logged, and recorded using a camera. Between each task, a rest period allowed the HR to recover close to the resting level to ensure variability in measured HR between tasks. If the participant was not able to perform a wheelchair activity independently because of their impairment, the task was not executed. After the activities were completed, a 30-minute upper-body strength exercise was performed. Exercises and resistances were chosen based on the participants' preferences and physical capabilities. All strength exercises were performed with sets of 8-12 repetitions, and each set was repeated 3 times in total. After each set, there was a rest period that lasted between 90 and 120 seconds before the next set was started. The strength exercise block was not executed if the participant was not able to perform strength exercises because of an upper-body injury or impairment.

Data analyses

Missing data and synchronization

On the basis of expert evaluation, all data of 8% (4/48) individuals were excluded. Of the 4 individuals, data for 2 (50%) individuals were excluded because of poor Polar H7 HR monitor connection throughout the whole measurement, data for 1 (25%) were excluded owing to battery failure of the Polar H7 HR monitor, and data for 1 (25%) were excluded because of the loss of Fitbit Charge 2 data. In total, the HR data of 92% (44/48) of participants were analyzed. In addition, approximately 0.6% of the data were excluded from 13% (6/48) of participants because of invalid samples (temporary loss of Polar H7 HR monitor connection). In total, 21,732 valid HR samples from both devices were used for analysis. The data of the 2 devices with different sampling rates were synchronized by relating the HR monitored by the reference device (ie, Polar H7 HR monitor) to that of the investigational device (ie, Fitbit Charge 2) that was closest in time. Consequently, data were labeled with one of the three activity categories: rest, wheelchair activities (including resting time between the activities and before the strength exercises started), and strength exercises (including resting time between the exercises) based on logbook data and video recordings.

Statistical Analyses

All statistical analyses were performed in R (version 3.6.1; R Foundation for Statistical Computing) using R Studio (version 1.2.1335). To assess error, the mean difference between the Polar H7 HR monitor and Fitbit Charge 2 HR samples was calculated, resulting in the mean error. In addition, the mean absolute error (MAE) and the MAPE were evaluated. As stated by the American National Standards Institute, the accuracy of HR monitors should be within –10% to +10% of the input rate or –5 to +5 beats per minute (bpm), whichever is greater [31]. In alignment with these standards, we considered a MAPE of –10% to +10% as an acceptable error rate. Following Nelson and Allen [17], outliers were not removed to evaluate the accuracy of consumer use conditions. Bland-Altman plots with 95% limits of agreement (LoA) were produced using the BlandAltmanLeh R package [32]. The Bland-Altman plots and LoA are the suggested methods for analyzing the agreement between 2 measurement devices [33–36]. These plots were inspected to assess systematic biases over the entire HR range and to assess the magnitude of such biases and whether Fitbit Charge 2 overestimated or underestimated HR compared with the Polar H7 HR monitor. Finally, in line with previous wearable validation studies [17,33], Lin concordance correlation coefficients (CCCs) [37] were calculated using the DescTools R package [38]. These correlation coefficients provide information on the association and strength of the linear relationships between the reference device and investigational device. According to Nelson and Allen [17], the strength of agreement can be interpreted based on the following: CCC<0.5 indicates a weak association, CCC between 0.5 and 0.7 indicates a moderate association, and CCC>0.7 relates to a strong association.

Results

Descriptives

Table 1 shows the demographic characteristics of the 77% (34/44) wheelchair users with SCI and 23% (10/44) participants without SCI included in the analyses. Table 2 shows the descriptive statistics for the 21,732 HR samples measured by the Polar H7 HR monitor and the Fitbit Charge 2. These samples were taken during rest (1168 HR samples over a 5-minute period), wheelchair activities (12,016 HR samples), and strength exercises (8548 HR samples). In addition, the distributions in the HR samples are displayed visually in the violin plots shown in Figure 1. The violin plot displays the mirrored density plot in addition to the box plot, which displays summary statistics, such as the median and IQR. As shown in Table 2, the range of the HR samples from Polar H7 was wider than the HR estimates produced by the Fitbit Charge 2. The differences in the range of HRs became more pronounced when the lesion was above T5. However, further investigation showed that the range produced by the Polar H7 and Fitbit Charge 2 was quite similar for people with SCI above T1.

Table 1. Demographic characteristics of participants (N=44).

Characteristics	Lesion level					
	All lesions (n=34)	**Below T5a (n=16)**	**T5 and above (n=18)**	**T1b – T5 (n=10)**	**Above T1 (n=8)**	**No SCIc (n=10)**
Gender						
Female	9	5	4	2	2	3
Male	25	11	14	8	6	7
Age (years), mean (SD)	48.9 (12)	49.3 (13.7)	48.4 (10.9)	50.0 (9.9)	46.5 (12.5)	50.8 (10.1)
AIS (A/B/C/D)[d]	14/3/2/15	6/0/1/9	8/3/1/6	8/0/0/2	0/3/1/4	N/A[e]
Time since injury (years), mean (SD)	14.7(11.6)	15.9 (13.3)	13.6 (10.1)	15.0 (11.7)	11.9 (8.1)	N/A
BMI, mean (SD)	24.2 (4.1)	23.5 (4)	24.7 (4.3)	25.7 (4.8)	23.6 (3.5)	26.0 (3.4)

[a]T5: fifth thoracic vertebrae.
[b]T1: first thoracic vertebrae.
[c]SCI: spinal cord injury.
[d]AIS: American Spinal Cord Injury Association Impairment Scale score.
[e]N/A: not applicable.

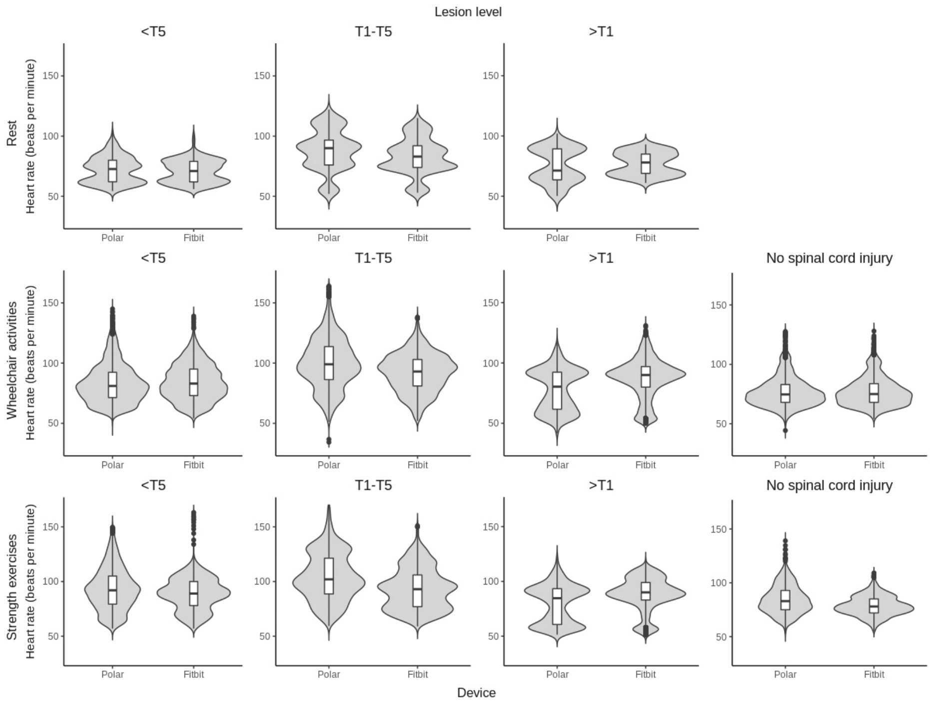


Figure 1. Violin plots of heart rate observations for Polar H7 and Fitbit Charge 2 divided by intensity from top to bottom in rest, wheelchair activities and strength exercise and divided by lesion level from left to right in lesion <T5, T1-T5, >T1, no spinal cord injury. Mean heart rate in beats per minute and IQRs are shown together with the distributions. T1: first thoracic vertebrae; T5: fifth thoracic vertebrae.

Table 2. Descriptive statistics of heart rate (HR) samples per activity, device, and lesion level.

Lesion level	HR samples	Polar H7 HR monitor, mean HR (SD; range)	Fitbit Charge 2, mean HR (SD; range)
All activities			
All included	21,732	85.7 (19.7; 34.3–169.7)	85.6 (15.7; 50–163)
All lesions	17,211	89.0 (20.7; 34.3–169.7)	87.6 (16.2; 50–163)
<T5[a]	8172	86.3 (18.1; 48–149.7)	85.2 (15.3; 54–163)
>T5	9039	91.4 (22.4; 34.3–169.7)	89.9 (16.6; 50–151)
T1[b]-T5	5324	100.5 (21.2; 34.3–169.7)	91.8 (16.9; 52–151)
>T1	3715	78.3 (17.1; 41.7–121.7)	87.1 (15.7; 50–131)
No SCI[c]	4521	80.5 (13.3; 44.3–139)	77.8 (10.7; 54–128)
Rest			
All lesions	1168	78.2 (15.5; 50.3–122)	76.2 (12.7; 53–115)
<T5	538	72.0 (10.7; 54.3–103.3)	70.7 (9.3; 56–102)
>T5	630	83.6 (17; 50.3–122)	80.8 (13.4; 53–115)
T1-T5	397	88.3 (16.8; 52–122)	83 (14.8; 53–115)
>T1	233	75.6 (14; 50.3–102)	77 (9.3; 61–93)
Wheelchair activities			
All included	12,016	85.3 (19.2; 34.3–164)	85.4 (15.8; 50–139)
All lesions	9654	87.4 (20; 34.3–164)	87.5 (15.9; 50–139)
<T5	4434	83.1 (16.1; 48–145)	84.3 (15.0; 54–139)
>T5	5220	91 (22.2; 34.3–164)	90.2 (16.2; 50–138)
T1-T5	3119	99.8 (20.7; 34.3–164)	92.1 (15.8; 52–138)
>T1	2101	77.8 (17.3; 41.7–118.7)	87.3 (16.3; 50–131)
No SCI	2362	76.9 (12.5; 44.3–127.7)	77.0 (12; 54–128)
Strength exercises			
All included	8548	91.1 (20; 51.3–169.7)	87.1 (15.5; 51–163)
All lesions	6389	93.4 (21.4; 51.3–169.7)	90 (16.2; 51–163)
<T5	3200	93.6 (23.4; 51.3–169.7)	88.8 (14.9; 57–163)
>T5	3189	93.1 (19.2; 57–149.7)	91.2 (17.3; 51–151)
T1-T5	1808	104.4 (21.8; 59.3–169.7)	93.2 (18.6; 59–151)
>T1	1381	79.6 (17.3; 51.3–121.7)	88.5 (15; 51–119)
No SCI	2159	84.4 (13.1; 53.3–139)	78.6 (9.1; 55–109)

[a]T5: fift thoracic vertebrae.
[b]T1: first thoracic vertebrae.
[c]SCI: spinal cord injury.

Mean absolute error

Overall, the Fitbit Charge 2 had a mean percentage error rate of 12.99% for people with SCI (Table 3), which is too high considering the standard acceptable MAPE is –10% to +10%. The MAPE of people with a lesion below T5 and between T1 and T5 was comparable with 11.16% and 10.16%, respectively, but for people with a lesion above T1, the MAPE was considerably higher (20.43%). People without SCI showed slightly better MAPE (8.09%) compared with people with lesions below T5 and between T1 and T5, as the MAPE was within the standard acceptable range of –10% to +10%. The MAPE was dependent on the type of activity performed by people with SCI. For rest, the overall MAPE was 6.5%, whereas the MAPE increased with the intensity of the activity to 12.97% for wheelchair activities and 14.2% for strength exercises. A similar trend was found in people without SCI, where the MAPE for strength exercise (8.39%) was slightly higher than the MAPE for wheelchair activities (7.82%). For each activity, a pattern exists where the MAPE increased with higher lesion levels. Taken together, the MAPE of the Fitbit Charge 2 only seemed within the acceptable range for people with SCI during rest. With higher lesion levels, Fitbit Charge 2 HR measurements were more off relative to the Polar H7 HR estimates.

Bland-Altman analysis and 95% Limits of Agreement

Table 3 shows the results from the Bland-Altman analysis, and Supplementary Appendix 1 shows the Bland-Altman plots. Across all lesion levels and activities, the mean error of the Fitbit Charge 2 was –1.3 (SD 17) bpm (lower LoA-upper LoA: –34.7 to 32.1 bpm) and MAE was 11.1. People without SCI showed a slightly larger mean error of –2.7 (SD 10.8) bpm (lower LoA-upper LoA: –23.9 to 18.5 bpm) but a smaller MAE of 7. Less agreement was observed in the group with a higher lesion level—mean error –1.1 (SD 14.7) bpm for the group with SCI lesions below T5 (lower LoA-upper LoA: –30 to 27.8 bpm), mean error –8.7 (SD 15.7) bpm (lower LoA-upper LoA: –39.3 to 22 bpm) for the group with SCI lesions between T1 and T5, and mean error 8.8 (SD 18.4) bpm (lower LoA-upper LoA: –27.3 to 44.8 bpm) for those with SCI lesions above T1. Although there were some outliers, Fitbit Charge 2 did not seem to systematically overestimate or underestimate HR values during rest in people with SCI. For the group with SCI lesions below T5, all outliers shown in Bland-Altman plots in Supplementary Appendix 1 during all 3 activities were from 3 separate participants. During rest, the overall mean error for people with SCI was –2.1 (SD 9) bpm (lower LoA-upper LoA: –19.7 to 15.6 bpm). Here, the agreement seemed lowest for the group with an SCI between T1-T5 with a mean error of –5.2 (SD 9.2) bpm (lower LoA-upper LoA: –23.3 to 12.8 bpm) compared with a mean error of –1.2 (SD 8.3) bpm (lower LoA-upper LoA: –17.4 to 14.9 bpm) for those with an SCI below T5 and a mean error of 1.5 (SD 8.6) bpm (lower LoA-upper LoA: –15.3 to 18.2 bpm) for those with an SCI above T1. In contrast, investigation of the plots presented in Supplementary Appendix 1 showed that during wheelchair activities and strength exercises, a trend toward overestimation for values below

100 bpm and an underestimation for observations with higher bpm was present. These trends seemed more pronounced during the strength exercises where the mean error was −3.4 (SD 18.8) bpm (lower LoA-upper LoA: −40.1 to 33.4 bpm) compared with an overall mean error of 0.1 (SD 16.4) bpm (lower LoA-upper LoA: −32.1 to 32.3 bpm) during wheelchair activities. A similar trend was found during strength exercise in those without an SCI, with a mean error of −5.8 (SD 10.6) bpm (lower LoA-upper LoA: −26.6 to 14.9 bpm) for strength exercise compared with a mean error of 0.1 (SD 10.2) bpm (lower LoA-upper LoA: −19.9 to 20.2 bpm) for wheelchair activities. Overall, Bland-Altman plots showed a trend toward overestimation of HR values for observations between 80 and 100 bpm in people with SCI lesions below T5. This was, to a lesser extent, also observed in general for people with SCI lesions above T1. In contrast, the Fitbit Charge 2 mostly underestimated the HR values of observations with ≥80 bpm in people with SCI between T1-T5.

Concordance class correlation

Overall, across all activities and all included groups, the Fitbit Charge 2 had a moderate agreement with the Polar H7 HR monitor (CCC=0.596, 95% CI 0.587-0.604). During rest, this agreement was stronger (CCC=0.791, 95% CI 0.770-0.810) and as intensity increased, this agreement became weaker; during wheelchair activities $CCC_{activities}$=0.615 (95% CI 0.605-0.626) and during strength exercises $CCC_{strength}$=0.531 (95% CI 0.517-0.545). Overall, the agreement was stronger for those with an SCI lower than T1 or no SCI and became much weaker for the group with SCI above T1: CCC_{noSCI}=0.585 (95% CI 0.567-0.603), $CCC_{<T5}$=0.613 (95% CI 0.599-0.626), CCC_{T1-T5}=0.605 (95% CI 0.590-0.620), and $CCC_{>T1}$=0.328 (95% CI 0.302-0.353). Agreement was weak for people with a lesion above T1 during wheelchair activities ($CCC_{>T1activities}$=0.354, 95% CI 0.321-0.386) and strength exercises ($CCC_{>T1strength}$=0.238, 95% CI 0.195-0.281). For lesions between T1 and T5 and lesions below T5, the agreement was moderate. Moderate ($CCC_{no\ SCI\ activities}$=0.653, 95% CI 0.629-0.675) to low ($CCC_{no\ SCIstrength}$=0.490, 95% CI 0.464-0.516) agreements were found for those without SCI, as shown in Table 4.

Table 3. Device error statistics.

Lesion level	Heart rate samples	Error Fitbit Charge 2			Bland-Altman analysis	
	MAE[a]	MAPE[b] (%)	ME[c] (SD)	Lower LoA[d]	Upper LoA	
All activities						
All included	21,732	10.2	11.97	-1.6 (16)	-32.9	29.7
All lesions	17,211	11.1	12.99	-1.3 (17)	-34.7	32.1
<T5[e]	8172	9.6	11.16	-1.1 (14.7)	-30	27.8
>T5	9039	12.4	14.64	-1.5 (18.9)	-38.5	35.5
T1[f]-T5	5324	11.6	10.60	-8.7 (15.7)	-39.3	22
>T1	3715	13.7	20.43	8.8 (18.4)	-27.3	44.8
No SCI[g]	4521	7	8.09	-2.7 (10.8)	-23.9	18.5
Rest						
All lesions	1168	5.2	6.5	-2.1 (9)	-19.7	15.6
<T5	538	4.1	5.41	-1.2 (8.3)	-17.4	14.9
>T5	630	6.2	7.43	-2.7 (9.5)	-21.4	15.9
T1-T5	397	6.2	6.27	-5.2 (9.2)	-23.3	12.8
>T1	233	6.2	9.39	1.5 (8.6)	-15.3	18.3
Wheelchair activities						
All included	12,016	9.9	11.96	0.1 (15.4)	-30.1	30.3
All lesions	9654	10.7	12.97	0.1 (16.4)	-32.1	32.3
<T5	4434	9.2	11.29	1.2 (14.3)	-26.8	29.1
>T5	5220	12	14.4	-0.8 (18)	-36.1	34.6
T1-T5	3119	10	10.33	-7.7 (14.2)	-35.6	20.2
>T1	2101	13.5	20.43	9.5 (18.2)	-26.3	45.2
No SCI	2362	6.3	7.82	0.1 (10.2)	-19.9	20.2
Strength exercises						
All included	8548	11.5	12.73	-4.0 (17.1)	-37.5	29.5
All lesions	6389	12.7	14.2	-3.4 (18.8)	-40.1	33.4
<T5	3200	11.1	11.94	-4.3 (15.6)	-34.9	26.3
>T5	3189	14.4	16.47	-2.5 (21.4)	-44.4	39.5
T1-T5	1808	13.8	12.03	-11.2 (18.5)	-47.5	25.2
>T1	1381	15.1	22.29	8.9 (19.5)	-29.3	47.1
No SCI	2159	7.7	8.39	-5.8 (10.6)	-26.6	14.9

[a]MAE: mean absolute error.
[b]MAPE: mean absolute percent error.
[c]ME: mean error.
[d]LoA: limits of agreement.
[e]T5: fifth thoracic vertebrae.
[f]T1: first thoracic vertebrae.
[g]SCI: spinal cord injury.

3

Table 4 Concordance class correlation based on lesion groups and activities.

Lesion level	Heart rate samples	Concordance class correlation (95% CI)
All activities		
All included	21,732	0.596 (0.587-0.604)
All lesions	17,211	0.577 (0.567-0.586)
<T5[a]	8172	0.613 (0.599-0.626)
>T5	9039	0.541 (0.527-0.554)
T1[b]-T5	5324	0.605 (0.590-0.620)
>T1	3715	0.328 (0.302-0.353)
No SCI[c]	4521	0.585 (0.567-0.603)
Rest		
All lesions	1168	0.791 (0.770-0.810)
<T5	538	0.659 (0.609-0.703)
>T5	630	0.792 (0.764-0.817)
T1-T5	397	0.788 (0.751-0.820)
>T1	233	0.736 (0.684-0.780)
Wheelchair activities		
All included	12,016	0.615 (0.605-0.626)
All lesions	9654	0.586 (0.573-0.599)
<T5	4434	0.577 (0.558-0.597)
>T5	5220	0.567 (0.550-0.584)
T1-T5	3119	0.645 (0.627-0.663)
>T1	2101	0.354 (0.321-0.386)
No SCI	2362	0.653 (0.629-0.675)
Strength exercises		
All included	8548	0.531 (0.517-0.545)
All lesions	6389	0.503 (0.486-0.520)
<T5	3200	0.567 (0.545-0.534)
>T5	3189	0.457 (0.431-0.482)
T1-T5	1808	0.505 (0.475-0.534)
>T1	1381	0.238 (0.195-0.281)
No SCI	2159	0.490 (0.464-0.516)

[a]T5: fifth thoracic vertebrae.

[b]T1: first thoracic vertebrae.

[c]SCI: spinal cord injury.

Discussion

Principal Findings

This is, to our knowledge, the first study to assess the HR accuracy of Fitbit Charge 2 in people with SCI, or more specifically, to assess the effects of lesion level on PPG-based HR accuracy. With an overall MAPE of 12.99% for the Fitbit Charge 2, the standard acceptable error of –10% to +10% was not met, and the outcomes were worse than in earlier research in able-bodied populations [17,20]. As the intensity of the activity increased, the HR accuracy of Fitbit Charge 2 worsened, which is in line with previous research [18–20]. Moreover, there seems to be a clear effect of lesion level, as the highest lesion group (>T1) showed drastically lower accuracy on Fitbit HR recordings on all intensities, compared with lower lesion level groups. This could possibly contribute to a more severely affected sympathetic innervation.

Compared with previous research in able-bodied individuals, our findings showed poorer outcomes for both MAPE and agreement rate during wheelchair activities and strength exercises. Previous research on the accuracy of HR measurements of the Fitbit Charge 2 that included similar activities (seated rest, activities of daily living, strength exercises) showed a MAPE range of 5.93% to 9.88% in able-bodied individuals. A similar range was found in this study in people without SCI (7.82%-8.39%) [17,20]. In all people with SCI, the MAPE range varied between 6.5% and 14.2%. During seated rest, our findings showed a stronger association (CCC=0.791) between the Fitbit Charge 2 and Polar H7 HR monitor compared with a moderate association in previous research (CCC=0.561) [17]; however, agreement and error in all other activities showed poorer results and worsened as intensity increased in people with SCI. The reduced accuracy with increasing intensities is in line with the literature [18,19], but accuracy worsened more in people with SCI during wheelchair activities (CCC=0.586; MAPE 12.97%) and strength exercises (CCC=0.503; MAPE 14.2%) than in people without SCI during wheelchair activities (CCC=0.653; MAPE 7.82%) and strength exercises (CCC=0.490; MAPE 8.39%) and previous literature (activities of daily living: CCC=0.739; MAPE 8.29%; strength exercise: CCC=0.72; MAPE 9.8% [17,20]). This could, at least in part, explain the overall poorer accuracy of the Fitbit Charge 2 during wheelchair activities in people with and without SCI in this study compared with previous findings in able-bodied individuals. However, this would not explain the drastically decreased HR accuracy of the Fitbit Charge 2 in the higher lesion level (>T1) group. Therefore, it is very likely that a more severely imbalanced ANS negatively affects the accuracy [39]. This could at least in part explain the overall poorer accuracy of the Fitbit Charge 2 during wheelchair activities in people with SCI and without SCI in this study compared to previous findings in able-bodied individuals. However, this would not explain the drastically decreased HR accuracy of the Fitbit Charge 2 in the higher lesion level (>T1) group. Therefore, it is very likely that a more severe imbalanced ANS affects the accuracy in a negative way [26].

It is remarkable that the T1-T5 group showed no clear difference from the <T5 group, as the sympathetic pathway is affected at lesion levels above T6 and an imbalance between the sympathetic and parasympathetic system is most likely present, which controls HR and blood pressure [24]. As there is a major difference between Polar H7 and Fitbit Charge 2 in the technique used to measure the obtained HR outcomes, it seems likely that this difference causes a drop in accuracy and agreement during the Fitbit Charge 2 HR recording. Because Fitbit Charge 2 HR recording is based on blood pressure differences, and autonomic control of the blood vessels in the upper body is controlled between segments T1 and T4, it was expected to observe differences in the T1-T5 group as well as in the >T1 group compared with the <T5 group. However, it appears that as long as there is some innervation left and not all sympathetic innervation of the blood vessels is affected, HR accuracy measured by PPG is only slightly reduced. The accuracy only seems to drop at lesion levels above T1, as there is possibly no sympathetic innervation left of the blood vessels in the lower parts of the upper limbs [40]. In addition, people with tetraplegia are more likely to show lower blood pressure compared with people with paraplegia or able-bodied individuals caused by reduced sympathetic activity [41]. Therefore, hypotension is a common phenomenon among people with tetraplegia, which could possibly influence the accuracy of PPG-based HR recordings as it deviates from the regular expected signal [42,43].

The severity of reduced sympathetic innervation is not necessarily related to neurological lesion completeness, which is often expressed using the American Spinal Cord Injury Association Impairment Scale score. This scale is based on the presence of motor or sensory function, where a complete injury is defined as the absence of both motor and sensory function below the lesion, and an incomplete lesion is defined as any reduced presence of motor or sensory function below the lesion [44]. However, research has shown that this classification does not necessarily include autonomic function, because sympathetic activity has been detected in athletes with complete cervical SCI lesions [45]. Although lesion level clearly influences the ANS and, therefore, Fitbit Charge 2 HR accuracy, the effect of completeness of the lesion on motor, sensory, and autonomic function remains unknown. Therefore, future studies should test autonomic function separately from neurological lesions in people with SCI to gain better insight on the effect of autonomic function on HR accuracy based on PPG signals.

Strengths and limitations

A strength of this study was the relatively large sample size of people with SCI, in which the distribution among the different lesion level groups, which were based on physiological differences determined by the literature, was fairly even and the direct comparison between people with and without SCI [24,26,40]. Analyses were performed, when possible, according to the methodological approaches suggested by Nelson and Allen [17], van Lier et al [34], and Sartor et al [33]. Activities and exercises mimicked real-life situations, which increased the ecological validity. Participants with SCI performed the tasks in their own wheelchair, at their own speed in relatively short time bouts, representing real-life situations better than prolonged steady-state activities. A suitable wheelchair was provided to the participants without SCI. Outcomes were analyzed as a whole and divided by lesion group and rest, wheelchair activities, and strength exercises to gain insight on both the effect of intensity and lesion level on the accuracy.

However, there are some limitations to the design and analysis. The reference device used, a Polar H7 HR monitor, is not considered a gold standard. A 3-lead ECG HR monitor device would have served better as a reference device. However, the Polar H7 HR monitor shows a high correlation with a 3-lead ECG (Intraclass Correlation Coefficient=0.98) and is therefore a good alternative [30]. In addition, HR outcomes from both devices were provided without raw signals (raw ECG signals and interbeat intervals). Ideally, one would obtain all raw information as algorithms to convert raw signals into the reported HR are often confidential and unknown. Firmware versions were, therefore, reported to take into account any sealed changes in such algorithms and to allow for the replication of results. HR was collected at the highest possible sample rate for Fitbit Charge 2, as intraday time series access was provided by Fitbit for research purposes. As measurements were performed within a larger study on energy expenditure in people with SCI, the Polar H7 was connected to an indirect calorimetry device during measurements. The output provided by this device was given on a breath-by-breath basis, meaning the HR sample rate for the Polar H7 varied per minute and was determined by the breathing rate of the participant, which eventually provided a lower HR sample rate than preferred. The number of data points available for each activity to analyze reduced when the lesion level increased, as several participants were not able to perform certain wheelchair activities or strength exercises because of the severity of their impairment, present injuries, or risks. In addition, no information was collected on the environmental conditions or skin information that could possibly affect the PPG signal [33]. However, because all measurements were performed at the same location within the same rooms, temperature and light were similarly regulated during all the measurements. Unfortunately, no blood pressure data were collected during the measurement to strengthen our findings. Therefore, it is advisable to combine HR recordings together with continuous blood pressure data in future research to confirm our findings.

Practical implementations

HR data obtained with the PPG technique during activities, especially during high intensities in people with a high lesion level (>T1), could provide inaccurate HR data in people with SCI. Therefore, it is advised to avoid using PPG-based HR measurements for medical purposes in people with SCI with a cervical lesion level (>T1). However, despite a possible discrepancy in HR recordings, outcomes can still be of value in situations where the consequences of inaccurate HR data are low, for example, to get a global impression of energy expenditure and exercise intensity during physical activities in daily life.

Conclusions

The overall accuracy of the Fitbit Charge 2 HR measurements in people with SCI did not reach the standard acceptable error of –10% to +10%. With increasing intensity, the HR accuracy of the Fitbit Charge 2 was further reduced in people with SCI compared with its HR accuracy in able-bodied individuals. In addition, HR accuracy is related to lesion level, where a high SCI lesion (>T1) negatively affects HR accuracy. Accuracy seems to worsen more in high lesion levels with increasing intensities. A clear reduction in accuracy was found in the lesion group >T1 during wheelchair activities and strength exercises. This suggests that PPG-based HR accuracy is affected in people with SCI, as blood pressure responses during activity are possibly altered because of an affected ANS. Therefore, PPG-based HR measurements during activities should be taken with caution in people with SCI, especially in those with cervical SCI lesions.

Acknowledgements

This study was funded by Nederlandse Organisatie voor Wetenschappelijk Onderzoek, Nationaal Regieorgaan Praktijkgericht Onderzoek SIA, and the São Paulo Research Foundation under the big data and sports call 2016.

Conflict of interests

None declared.

References

1. Van Den Berg-Emons RJ, Bussmann JB, Stam HJ. Accelerometry-based activity spectrum in persons with chronic physical conditions. Arch Phys Med Rehabil; 2010 Dec;91(12):1856–1861. [doi: 10.1016/j.apmr.2010.08.018] [Medline:21112426]

2. Nevin AN, Steenson J, Vivanti A, Hickman IJ. Investigation of measured and predicted resting energy needs in adults after spinal cord injury: a systematic review. Spinal Cord 2016 Apr;54(4):248–253. [doi: 10.1038/sc.2015.193] [Medline:26690858]

3. Felleiter P, Krebs J, Haeberli Y, Schmid W, Tesini S, Perret C. Post-traumatic changes in energy expenditure and body composition in patients with acute spinal cord injury. J Rehabil Med 2017 Jul;49(7):579–584. [doi:10.2340/16501977-2244] [Medline:28657645]

4. Buchholz AC, McGillivray CF, Pencharz PB. Differences in resting metabolic rate between paraplegic and able-bodied subjects are explained by differences in body composition. Am J Clin Nutr 2003 Feb;77(2):371–378. [doi:10.1093/ajcn/77.2.371] [Medline:12540396]

5. Chun SM, Kim H-R, Shin HI. Estimating the Basal metabolic rate from fat free mass in individuals with motor complete spinal cord injury. Spinal Cord 2017 Sep;55(9):844-847. [doi:10.1038/sc.2017.53] [Medline:28534498]

6. Weaver FM, Collins EG, Kurichi J, Miskevics S, Smith B, Rajan S, Gater D. Prevalence of obesity and high blood pressure in veterans with spinal cord injuries and disorders: A retrospective review. Am J Phys Med Rehabil 2007 Jan;86(1):22–29. [doi:10.1097/phm.0b013e31802b8937] [Medline:17304685]

7. Myers J, Lee M, Kiratli J. Cardiovascular disease in spinal cord injury: An overview of prevalence, risk, evaluation, and management. Am J Phys Med Rehabil 2007 Feb;86(2):142–152. [doi:10.1097/PHM.0b013e31802f0247] [Medline:17251696]

8. Vincent JL. Understanding cardiac output. Crit Care 2008;12(4):174. [doi:10.1186/cc6975] [Medline: 18771592]

9. Gordan R, Gwathmey JK, Xie L-H. Autonomic and endocrine control of cardiovascular function. World J Cardiol 2015 Apr;7(4):204-214. [doi:10.4330/wjc.v7.i4.204] [Medline:25914789]

10. Achten J, Jeukendrup AE. Heart Rate Monitoring Applications and Limitations. Sport med 2003;33(7):517–538. [doi:10.2165/00007256-200333070-00004] [Medline:12762827]

11. Allen J. Photoplethysmography and its application in clinical physiological measurement. Physiol Meas 2007 Mar;28(3):1-39. [doi:10.1088/0967-3334/28/3/R01] [Medline:17322588]

12. Sviridova N, Sakai K. Human photoplethysmogram: New insight into chaotic characteristics. Chaos Solit Fract 2015 Aug;77:53–63. [doi:10.1016/j.chaos.2015.05.005]

13. Alnaeb M, Alobaid N, Seifalian A, Mikhailidis D, Hamilton G. Optical Techniques in the Assessment of Peripheral Arterial Disease. Curr Vasc Pharmacol 2007 Jan;5(1):53–59. [doi:10.2174/157016107779317242]

14. Zhang Y, Liu B, Zhang Z. Combining ensemble empirical mode decomposition with spectrum subtraction technique for heart rate monitoring using wrist-type photoplethysmography. Biomed Sign Process Control 2015 Aug;21:119–125. [doi:10.1016/j.bspc.2015.05.006]

15. Castaneda D, Esparza A, Ghamari M, Soltanpur C, Nazeran H. A review on wearable photoplethysmography sensors and their potential future applications in health care. Int J Biosens Bioelectron 2018;4(4):195–202. [doi:10.15406/ijbsbe.2018.04.00125] [Medline:30906922]

16. de Zambotti M, Baker FC, Willoughby AR, Godino JG, Wing D, Patrick K, Colrain IM. Measures of sleep and cardiac functioning during sleep using a multi-sensory commercially-available wristband in adolescents. Physiol Behav May; 2016;158:143–149. [doi:10.1016/j.physbeh.2016.03.006]

17. Nelson BW, Allen NB. Accuracy of consumer wearable heart rate measurement during an ecologically valid 24-hour period: Intraindividual validation study. J Med Internet Res Mhealth Uhealth 2019;21(3):1–16. [doi:10.2196/10828] [Medline:26969518]

18. Boudreaux BD, Hebert EP, Hollander DB, Williams BM, Cormier CL, Naquin MR, Gillan WW, Gusew EE, Kraemer RR. Validity of Wearable Activity Monitors during Cycling and Resistance Exercise. Med Sci Sports Exerc. 2018 Mar;50(3) 624-633 [doi:10.1249/MSS.0000000000001471] [Medline: 29189666]

19. Dooley EE, Golaszewski NM, Bartholomew JB. Estimating Accuracy at Exercise Intensities: A Comparative Study of Self-Monitoring Heart Rate and Physical Activity Wearable Devices. JMIR mHealth uHealth 2017 Mar;5(3):e34. [doi:10.2196/mhealth.7043] [Medline:28302596]

20. Reddy RK, Pooni R, Zaharieva DP, Senf B, El Youssef J, Dassau E, Doyle FJ, Clements MA, Rickels MR, Patton SR, Castle JR, Riddell MC, Jacobs PG. Accuracy of wrist-worn activity monitors during common daily physical activities and types of structured exercise: Evaluation study. JMIR mHealth uHealth 2018 Dec;6(12):e10338. [doi:10.2196/10338] [Medline:30530451]

21. Wright SP, Hall Brown TS, Collier SR, Sandberg K. How consumer physical activity monitors could transform human physiology research. Am J Physiol - Regul Integr Comp Physiol 2017 Dec;312(3): 358–367. [doi:10.1152/ajpregu.00349.2016] [Medline:28052867]

22. Dias D, Cunha J. Wearable health devices—vital sign monitoring, systems and technologies. Sensors (Basel) 2018 Jul;18(8):2414. [doi:10.3390/s18082414] [Medline:30044415]

23. Perez M V., Mahaffey KW, Hedlin H, Rumsfeld JS, Garcia A, Ferris T, Apple Heart Study Investigators. Large-scale assessment of a smartwatch to identify atrial fibrillation. N Engl J Med 2019 Nov;381(20):1909–1917. [doi:10.1056/NEJMoa1901183] [Medline:31722151]

24. Grigorean V, Sandu A, Popescu M, Iacobini MA, Stoian R, Neascu C, Strambu V, Popa F. Cardiac dysfunctions following spinal cord injury. J Med Life 2009;2(2):133–145. [Medline:20108532]

25. Bent B, Goldstein BA, Kibbe WA, Dunn JP. Investigating sources of inaccuracy in wearable optical heart rate sensors. npj Digit Med 2020;3:18 [doi:10.1038/s41746-020-0226-6] [Medline:32047863]

26. Grimm DR, DeMeersman RE, Garofano RP, Spungen AM, Bauman WA. Effect of provocative maneuvers on heart rate variability in subjects with quadriplegia. Am J Physiol-Heart Circul Physiol 1995 Jun;268(6):2239-2245. [doi:10.1152/ajpheart.1995.268.6.h2239]

27. Method Comparison and Bias Estimation Using Patient Samples; Approved Guideline - Second Edition. Clinical and Laboratory Standards Institute [CLSI]. 2002. URL: https://webstore.ansi.org/standards/clsi/clsiep09a2 [accessed 2021-12-13]

28. Teasell RW, Arnold JO, Krassioukov A, Delaney GA. Cardiovascular consequences of loss of supraspinal control of the sympathetic nervous system after spinal cord injury. Arch Phys Med Rehabil 2000 Apr;81(4):506–516. [doi:10.1053/mr.2000.3848] [Medline:10768544]

29. Sachdeva R, Nightingale TE, Krassioukov AV. The blood pressure pendulum following spinal cord injury: implications for vascular cognitive impairment. Int J Mol Sci 2019 May;20(10):2464. [doi: 10.3390/ijms20102464] [Medline:31109053]

30. Pasadyn SR, Soudan M, Gillinov M, Houghtaling P, Phelan D, Gillinov N, et al. Accuracy of commercially available heart rate monitors in athletes: A prospective study. Cardiovasc Diagn Ther 2019 Aug;9(4):379–385. [doi:10.21037/cdt.2019.06.05] [Medline:31555543]

31. The Association for Advancement of Medical Instrumentation. American National Standard. Cardiac monitors, heart rate meters, and alarms. Arlington; 2002.

32. Lehnert B. BlandAltmanLeh: Plots (slightly extended) Bland-Apltman Plots. Cran.R-Project. 2015. URL: https://cran.r-project.org/package =BlandAltmanLeh/index.html [accessed 2021-12-13]

33. Sartor F, Papini G, Elisabeth Cox LG, Cleland J. Methodological shortcomings of wrist-worn heart rate monitors validations. J Med Internet Res 2018 Jul;20(7):e10108. [doi:10.2196/10108] [Medline: 29967000]

34. van Lier HG, Pieterse ME, Garde A, Postel MG, de Haan HA, Vollenbroek-Hutten MM, et al. A standardized validity assessment protocol for physiological signals from wearable technology: methodological underpinnings and an application to the E4 biosensor. Behav Res Methods 2020 Apr;52(2):607–629. [doi:10.3758/s13428-019-01263-9] [Medline:31290128]

35. Zaki R, Bulgiba A, Nordin N, Azina Ismail A. A systematic review of statistical methods used to test for reliability of medical instruments measuring continuous variables. Iran J Basic Med Sci 2013 Jun;16(6):803–807. [Medline:23997908]

36. Altman DG, Bland JM. Measurement in medicine: the analysis of method comparison studies. Statistician 1983 Sep;32(3):307. [doi:10.2307/2987937]

37. Lin LI. A concordance correlation coefficient to evaluate reproducibility. Biometrics 1989 Mar;45(1):255–268. [doi:10.2307/2532051]

38. Signorell A. DescTools: tools for descriptive statistics. Cran.R-Project. 2020. URL:http://cran.r-project.org/package=DescTools [accessed 2021-12-13]

39. Teng XF, Zhang YT. The effect of contacting force on photoplethysmographic signals. Physiol Meas 2004 Oct;25(5):1323–1335. [doi:10.1088/0967-3334/25/5/020] [Medline:15535195]

40. West C, Alyahya A, Laher I, Krassioukov A. Peripheral vascular function in spinal cord injury: a systematic review. Spinal Cord 2013 Jan;51(1):10–19. [doi:10.1038/sc.2012.136] [Medline:23184028]

41. Mathias C, Frankel H. The cardiovascular system in tetraplegia and paraplegia. In: Frankel H, Bruyn G, Klawans H, Vinken P, editors. Spinal Cord Trauma, Handbook of Clinical Neurology. Amsterdam: Elsevier; 1992:435–456.

42. Lehmann K, Lane J, Piepmeier J, Batsford W. Cardiovascular abnormalities accompanying acute spinal cord injury in humans: incidence, time course and severity. J Am Coll Cardiol 1987 Jul;10(1):46–52. [doi:10.1016/S0735-1097(87)80158-4]

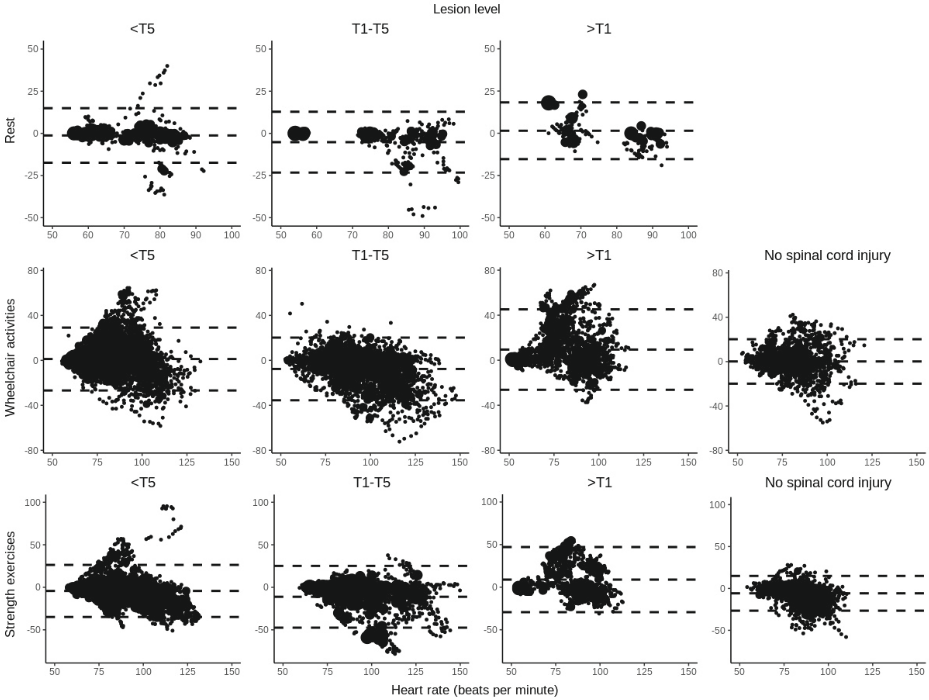
43. Lemay M, Bertschi M, Sola J, Renevey P, Parak J, Korhonen I. Chapter 2.3 - Application of optical heart rate monitoring. In: Wearable Sensors – Fundamentals, Implementation and Applications. Amsterdam: Elsevier; 2015: 105–129.

44. Kirshblum SC, Burns SP, Biering-Sorensen F, Donovan W, Graves DE, Jha A, et al. International standards for neurological classification of spinal cord injury (Revised 2011). J Spinal Cord Med 2013 Jul;34(6):535–546. [doi:10.1179/204577211x13207446293695]

45. West CR, Romer LM, Krassioukov A. Autonomic function and exercise performance in elite athletes with cervical spinal cord injury. Med Sci Sports Exerc 2013 Feb;45(2):261–267. [doi: 10.1249/MSS.0b013e31826f5099] [Medline: 22914247]

Supplementary appendix 1

Bland-Altman plots.



Abbreviations

ANS: autonomic nervous system

bpm: beats per minute

CCC: concordance correlation coefficient

ECG: electrocardiography

HR: heart rate

LoA: limits of agreement

MAE: mean absolute error

MAPE: mean absolute percentage error

PPG: photoplethysmography

SCI: spinal cord injury

T1: first thoracic vertebrae

T5: fifth thoracic vertebrae

Chapter 4

Mobile App (WHEELS) to Promote a Healthy Lifestyle in Wheelchair Users With Spinal Cord Injury or Lower Limb Amputation: Usability and Feasibility study

Published as: Hoevenaars D, Holla JFM, Te Loo L, Koedijker JM, Dankers S, Houdijk H, Visser B, Janssen TWJ, de Groot S, Deutekom M; WHEELS Study Group. Mobile App (WHEELS) to Promote a Healthy Lifestyle in Wheelchair Users With Spinal Cord Injury or Lower Limb Amputation: Usability and Feasibility Study. JMIR Form Res. 2021 Aug 9;5(8):e24909.

Abstract

Background: Maintaining a healthy lifestyle is important for wheelchair users' well-being, as it can have a major impact on their daily functioning. Mobile health (mHealth) apps can support a healthy lifestyle; however, these apps are not necessarily suitable for wheelchair users with spinal cord injury or lower limb amputation. Therefore, a new mHealth app (WHEELS) was developed to promote a healthy lifestyle for this population.

Objectives: The objectives of this study were to develop the WHEELS mHealth app, and explore its usability, feasibility, and effectiveness.

Methods: The WHEELS app was developed using the intervention mapping framework. Intervention goals were determined based on a needs assessment, after which behavior change strategies were selected to achieve these goals. These were applied in an app that was pretested on ease of use and satisfaction, followed by minor adjustments. Subsequently, a 12-week pre-post pilot study was performed to explore usability, feasibility, and effectiveness of the app. Participants received either a remote-guided or stand-alone intervention. Responses to semistructured interviews were analyzed using content analysis, and questionnaires (System Usability Score [SUS], and Usefulness, Satisfaction, and Ease) were administered to investigate usability and feasibility. Effectiveness was determined by measuring outcomes on physical activity, nutrition, sleep quality (Pittsburgh Sleep Quality Index), body composition, and other secondary outcomes pre and post intervention, and by calculating effect sizes (Hedges *g*).

Results: Sixteen behavior change strategies were built into an app to change the physical activity, dietary, sleep, and relaxation behaviors of wheelchair users. Of the 21 participants included in the pilot study, 14 participants completed the study. The interviews and questionnaires showed a varied user experience. Participants scored a mean of 58.6 (SD 25.2) on the SUS questionnaire, 5.4 (SD 3.1) on ease of use, 5.2 (SD 3.1) on satisfaction, and 5.9 (3.7) on ease of learning. Positive developments in body composition were found on waist circumference (*P*=.02, *g*=0.76), fat mass percentage (*P*=.004, *g*=0.97), and fat-free mass percentage (*P*=.004, *g*=0.97). Positive trends were found in body mass (*P*=.09, *g*=0.49), BMI (*P*=.07, *g*=0.53), daily grams of fat consumed (*P*=.07, *g*=0.56), and sleep quality score (*P*=.06, *g*=0.57).

Conclusions: The WHEELS mHealth app was successfully developed. The interview outcomes and usability scores are reasonable. Although there is room for improvement, the current app showed promising results and seems feasible to deploy on a larger scale.

Keywords: mHealth; mobile app; lifestyle; usability; feasibility; wheelchair users; spinal cord injury; lower limb amputation

Introduction

A healthy lifestyle is known to be beneficial for a person's well-being and happiness in many ways [1]. Healthy lifestyle behavior is especially important for wheelchair users owing to its major impact on their daily level of functioning [2]. Nevertheless, physical inactivity, obesity, and low vitality are common among wheelchair users with spinal cord injury (SCI) or lower limb amputation (LLA), which increase the risk of secondary health problems such as cardiovascular disease and can cause a reduced quality of life [3–9]. Therefore, it is important for wheelchair users to be encouraged to achieve and maintain a healthy lifestyle during and after inpatient rehabilitation [10–13]. Despite encouragement during inpatient rehabilitation, it appears to be difficult for wheelchair users with SCI or LLA to adopt or maintain the recommended physical activity levels and healthy diet after discharge [12,14–16]. Environmental factors such as fitness centers not having accessible toilets and personal factors such as lack of knowledge and motivation can play a role in this lack of physical activity. One of the barriers for maintaining a healthy lifestyle is the lack of professional guidance after discharge. Wheelchair users with SCI or LLA clearly express their need for such support [17,18], and guided interventions have shown positive effects for behavioral change and maintenance [19–21]. To save costs and time, mobile health (mHealth) tools could be used to support the professional in providing this additional guidance, which has been shown to be an effective method for changing behavior [22]. mHealth tools focus mainly on personal determinants of behavior. Although they cannot remove existing barriers in the physical or societal environment, they can increase the knowledge and skills to cope with these barriers.

mHealth provides the opportunity to stimulate, support, and monitor a healthy lifestyle at the individual and group levels [11]. Given that smartphones have become an integral part of our lives, mHealth seems to be a promising tool supporting healthy changes in physical activity, sedentary behavior, diet, relaxation, and sleep. A healthy lifestyle refers to the combination of healthy physical activity with appropriate dietary, relaxation, and sleep behaviors. Successful self-management apps have been developed for people with chronic conditions [23,24]. People tend to value mHealth apps that support goal-setting, and provide information and advice, feedback, self-monitoring tools, social support, and reinforcement [25]. The use of an appropriate combination of techniques to change lifestyle-related determinants mediates [26,27]. However, determinants of physical activity, nutrition, and sleep can vary among populations and are different in individuals with a disability [28]. To date, there is no mHealth app designed specifically for wheelchair users with SCI or LLA to target all of these behaviors simultaneously. Therefore, in the Wheelchair ExercisE and Lifestyle Study (WHEELS) project, an existing lifestyle app for healthy able-bodied people was adapted for wheelchair users with SCI and LLA based on the intervention mapping protocol [29].

Targeting behavior change specifically for wheelchair users includes overcoming additional social barriers, which was taken into account during development of the WHEELS app [30]. An intervention targeting the combination of physical activity and dietary behavior seems to be superior to an intervention targeting physical activity or diet alone in weight management and improving health [31,32]. Because poor sleep quality and lack of sleep have a negative association with weight regulation, it seems to be of added value to also target resting and sleep behavior [33–35]. Given the positive relations between physical activity, diet, and sleep behavior, as well as combining multiple healthy lifestyle features, a lifestyle app was designed in which physical activity, dietary, sleep, and resting behaviors were targeted simultaneously [35–37].

To evaluate this combined lifestyle app, a usability and effectiveness study was performed in wheelchair users with SCI or LLA. A multicomponent intervention, which is a combination of different intervention components such as an app combined with counseling, seems to be more effective than a stand-alone app intervention [25]. This raised the question as to whether this would also be the case among wheelchair users. Therefore, both a stand-alone and a remote-guided version of the mHealth intervention were applied during the intervention period. In the remote-guided version, personal guidance from a lifestyle coach was offered throughout the intervention period. The aims of this study were to: (1) describe the development of the WHEELS mHealth app; and (2) explore its usability, feasibility, and effectiveness.

Methods

Development of the mHealth Intervention Using Intervention Mapping

The WHEELS lifestyle app was developed using the intervention mapping framework for planning theory- and evidence-based health promotion programs [38]. This framework consists of six steps: (1) perform a needs assessment and state intervention goals; (2) construct matrices of change objectives; (3) choose theory- and evidence-based behavior change methods and practical applications to deliver them; (4) pretest, refine, and produce the program; (5) develop an implementation plan; and (6) create an evaluation plan. These six intervention mapping steps to plan a mobile lifestyle intervention for wheelchair users with SCI or LLA, focusing particularly on steps 1 to 4, are presented in detail in Supplementary Appendix 1.

App Description and Content

The WHEELS app is targeted toward wheelchair users with SCI or LLA to help them comply with the scientific exercise guidelines for adults with SCI [7]; achieve a healthy energy balance, and achieve a healthy balance between exercise and sleep/relaxation. In the app, wheelchair users are guided to these intervention goals by providing them knowledge and a format for setting personally meaningful subgoals and the functionalities described below. To work with the app, the user creates an account that they can personalize. Personal characteristics are used to provide feedback within the app (eg, height, body mass, and activity level are used to estimate resting energy expenditure). When logging in, users can navigate through the app from the home screen as shown in screenshot 1 in Figure 1. From the home screen, users can navigate to the “Individual exercises” and “Exercise program” tiles where exercises can be performed and scheduled in their personal agenda (Figure 1, screenshots 3 and 4). In the “Food” part, users receive an overview of their energy balance based on their nutrition intake and energy expenditure (Figure 1, screenshot 5). Nutrition plans and goals can be created (eg, losing weight) in which the app would guide the user through some steps toward a reasonable nutrition plan, resulting in a suggested daily energy intake. In the “Sleep & Relaxation” environment, exercises and knowledge are offered on balancing physical and mental load and relaxation. Behind the “Progress” tile, users are able to obtain insight and track changes in predefined health and fitness parameters such as weight and BMI. In addition, the “Community” section includes start instructions and four groups (exercise, nutrition, sleep and relaxation, lifestyle change tool) in which information and tips are posted over time (Figure 1, screenshot 2). A fifth group allows users to ask questions, share experiences and tips, and interact with other users. Finally, users are able join various challenges in which they can compare performances with each other (eg, a weekly 90-minute handcycle challenge) (Figure 1, screenshot 7).

Usability and Feasibility Study

Participants

To evaluate the usability and feasibility of the app, potential end users were invited to participate in the study. Recruitment took place by advertisement at patient associations gatherings, on social media, and within the rehabilitation centers Reade (Amsterdam, the Netherlands) and Heliomare (Wijk aan Zee, the Netherlands). Potential participants were included when all of the following criteria were met: chronic SCI (including spina bifida) or LLA (>1 year), wheelchair-dependent for longer (>500 m) distances, 18 years or older, sufficient knowledge of the Dutch language, and access to a smartphone or tablet connected to the internet. Potential participants were excluded when one of the following criteria was met: insufficient understanding of technology to benefit from the app; limited functioning in the arm/hand to operate a smartphone or tablet; presence of progressive disorders that can influence the outcomes; presence of psychiatric disorders; and negative outcome to unsupervised exercise based on a medical screening, including a graded exercise test. The target was to include 15 individuals with SCI and 15 individuals with LLA resulting in a sufficient sample size with a possible 10% dropout rate, based on the literature [39]. All participants provided written informed consent and ethical approval was granted by the local Medical Ethical Committee of Slotervaart Ziekenhuis-Reade (METC nr. P1761).

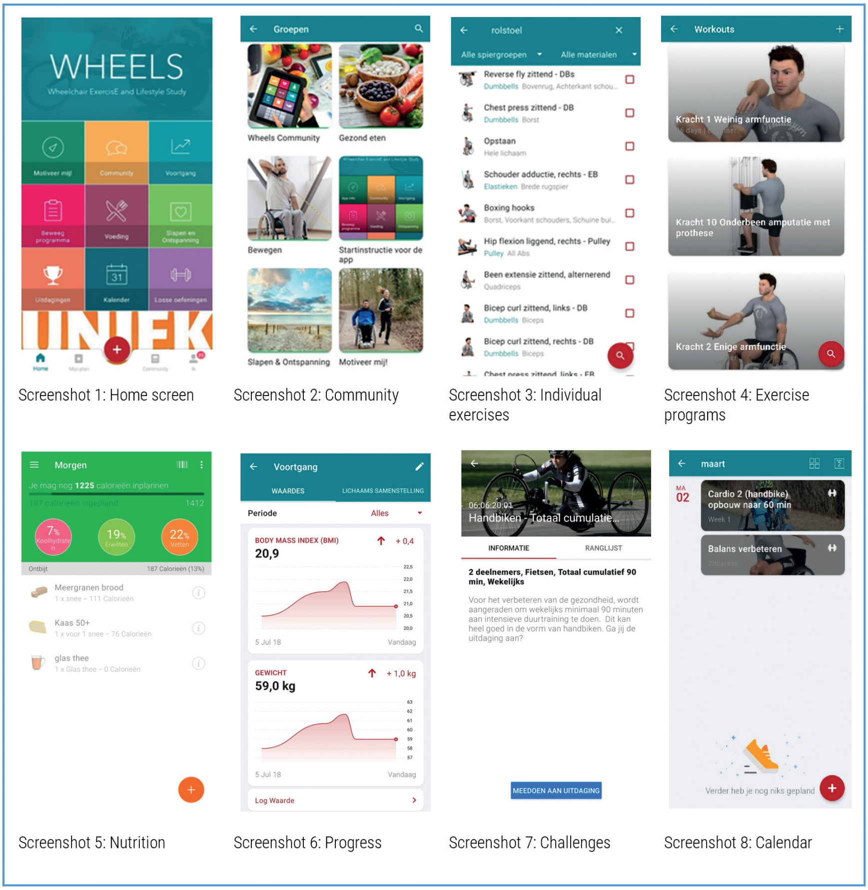


Figure 1. Structure overview of the WHEELS app.

Study Design and Protocol

Participants were asked to participate in a 12-week pre-post pilot study focusing on the usability and feasibility of the app. Block randomization stratified by disorder with a block size of one was used to equally allocate the participants to a stand-alone or remote-guided intervention group. The remote-guided group received guidance from a lifestyle coach during the 12-week intervention (figure 2). At the start of the study, the stand-alone group received an individual explanation and demonstration of the app from the researcher. During the study, this group was allowed to consult the researcher with any questions or difficulties regarding use of the app. The remote-guided group also received support at the start of the study, but additionally received remote guidance, consisting of an additional face-to-face consultation (30 minutes) at the start of the intervention and 10-15 minute contact moments after 3, 6, 9, and 12 weeks by phone, app, or email. The purpose of these contact moments was to discuss progress and to adjust the goals or the program if necessary. The two lifestyle coaches providing the supervision were 4th year students in Functional Exercise Therapy who were trained in motivational interviewing, assisted by an experienced rehabilitation professional from Reade or Heliomare who they could consult with any questions.

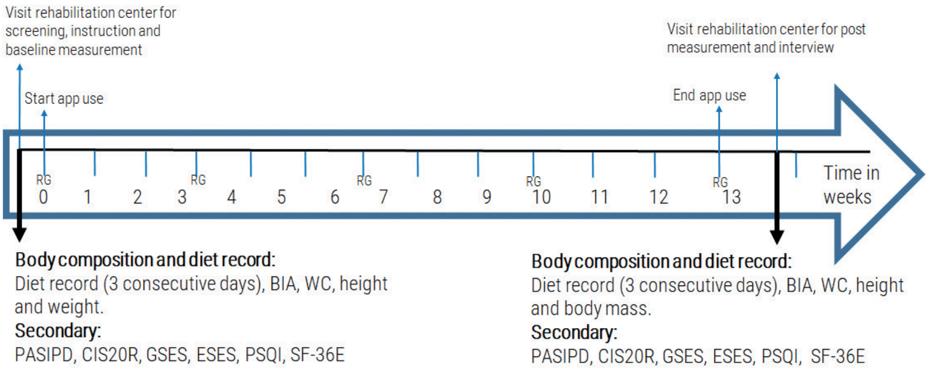


Figure 2. Schematic overview of measurements. BIA: bioimpedance analysis; CIS20R: checklist individual Strength; ESES: Exercise Self-Efficacy Scale for spinal cord injury; GSES: General Self-Efficacy Scale; PASIPD: Physical Activity Scale for Individuals with Physical Disabilities; PSQI: Pittsburgh Sleep Quality Index; RG: remote guidance; SF-36E: Short-Form 36 health survey; WC: waist circumference.

Owing to the design and nature of the study, it was not possible to blind participants or researchers. The participants kept a 3-day diet record during the same weeks as the scheduled pre and post measurements, which took place at a rehabilitation center. In addition, body composition was measured before and after the intervention, and participants were invited through email to complete an online questionnaire in Qualtrics to measure lifestyle and health-related quality of life. During the last visit, a semistructured interview was conducted and recorded.

Qualitative Evaluation: Usability and Feasibility

Topics evaluated to assess usability were: (1) usefulness, (2) ease of use, (3) satisfaction, (4) ease of learning, (5) motivation, (6) adherence, and (7) goals. In addition, semistructured interviews and questionnaires (System Usability Scale [SUS] [40] and Usefulness, Satisfaction, and Ease of Use [USE] [41] were used to gain insight into usability and feasibility.

The interviews were conducted by the same two researchers and lecturers in Sports Studies (LtL and JK) who instructed the participants on how to use the app at the start of the study. The interviews took place following the postintervention measurements in the rehabilitation center in a private room, lasting on average 30 minutes and were audio-recorded with consent of the participants. An interview guide, developed by the research team and partially based on the SUS and USE questionnaires and broader literature on behavior change [41–43], was used to structure the interview. After starting with the question "How experienced are you with using smartphone apps?" the following topics were discussed: goals, adherence, motivation, ease of use, satisfaction, and usability. The complete interview guide is provided in Supplementary Appendix 2.

The SUS questionnaire is a 10-item Likert scale providing an overall subjective assessment on usability of a product. An 11-point Likert scale was used with a score ranging from 0 ("strongly disagree") to 10 ("strongly agree"). A total score was calculated by rescaling the score to a total of 100, with a higher score indicating higher perceived usability [40]. A SUS score of 70 is considered to be average based on a wide range of interfaces [44].

Additionally, three out of four dimensions of the USE questionnaire were used to gain insight in the dimensions "ease of use," "ease of learning," and "satisfaction." Each dimension is composed of 11, 4, and 7 items, respectively. The dimension "usefulness" was left out as it overlapped strongly with the SUS questionnaire. An 11-point Likert scale was used with a score ranging from 0 ("strongly disagree") to 10 ("strongly agree") and averaged for each dimension [41].

Quantitative Evaluation

Nutritional Habits

The diet record took place on 3 consecutive days with one weekend day, which is considered one of the most reliable methods of dietary assessment [45]. Uncertainties about registered diet records (ie, unclear handwriting, unclear food proportions) were solved by contacting the participant. Diet records were analyzed based on the nutrition values of the recorded products as shown in the Dutch nutrient database Nederlands Voedingsstoffenbestand version 2019/6.0 [46] and averaged over at least 2 available days.

Body Composition

Body mass was determined to the nearest 0.1 kilogram by deducting the mass of the wheelchair from the total mass of the participant and wheelchair combined, measured with a wheelchair weighing scale (RS1010, Allscales Europe used at Reade; Detecto 6550 used at Heliomare). Height and waist circumference (WC) were measured with a tape measure to the nearest 0.5 centimeters with the participants in supine position on a treatment table. WC was determined by taking the average of three measurements. BMI (body mass/height^2) was calculated with the proposed equation of Himes [47] in the case of LLA, based on the relative body segmental mass determined by Osterkamp [48] to adjust for lost body mass. Fat mass and fat-free mass were measured with a Bodystat 1500MDD (used at Reade) bioelectrical impedance analysis (BIA) device or with a Bodystat 500 Touch (used at Heliomare) BIA device in supine position. The BIA electrodes were placed at the right side of the body after the participant was in supine position. In case of unilateral LLA on the right side, the left side was measured. Electrodes were attached on the hands and feet according to the user manual. The BIA formula of Kyle et al [49] was used to calculate the fat-free mass and fat mass percentages based on the measured reactance and resistance.

Physical Activity

Physical activity was measured by the Dutch Physical Activity Scale for Individuals with Physical Disabilities (PASIPD), a 12-item 7-day recall self-reported questionnaire evaluating physical activity level in individuals with a physical disability. The PASIPD outcome is the metabolic equivalents of task (MET) hours spent per day and was calculated according to the method of Washburn et al [50]. The score in MET (hours/day) can range from 0 to 182.3 and can differentiate significantly among various physical activity levels.

Self-Efficacy

The General Self-Efficacy Scale and Exercise Self-efficacy scale, which are valid and reliable 10-item questionnaires (4-point Likert scale, total scores range from 10 to 40, where a higher score represents a higher self-efficacy), were used to assess the general self-efficacy and coping ability in daily life and exercise self-efficacy [51–56].

Fatigue

The Checklist Individual Strength (CIS20R), a reliable self-reported questionnaire (20 questions answered on a 7-point Likert scale, total scores range from 20 to 140 where a higher score represents more severe fatigue), was used to measure multiple aspects of fatigue [56,57].

Sleep Quality

The Pittsburgh Sleep Quality Index (PSQI) is a valid self-reported questionnaire to evaluate overall sleep quality [58]. The questionnaire consists of 19 questions resulting in a global score between 0 and 21, which consists of seven component scores (ie, sleep quality, sleep onset latency, sleep duration, sleep efficiency, sleep disturbances, use of sleeping medication, and daytime dysfunction). A higher global score represents worse sleep quality. The PSQI is considered as a reliable and valid method to evaluate sleep quality [59].

Quality of Life

The short-form health survey enabled (SF-36E) questionnaire was constructed to measure health-related quality of life on eight different dimensions of health for individuals with a mobility impairment [60]. The eight dimensions are physical functioning, social functioning, physical role emotional role, mental health, vitality, bodily pain, general health, and health transition. Dimension scores are rescaled to a 0-100 score where a higher score represents a higher quality of life. The Dutch version of the SF-36E is considered as a reliable and valid tool for individuals with chronic disabilities [61].

Data Analysis

Qualitative Evaluation

The audio recordings were transcribed verbatim and analyzed using a content analysis approach [62]. After familiarizing with the data by listening to the interviews and reading the transcripts, initial codes were identified by labeling text segments (open coding). The open codes were a mix of inductive codes that arose from reading the transcripts and deductive codes that arose from the study aims and interview guide. The open codes were then organized in a thematic map by comparing them and categorizing them into codes and subcodes. Finally, the codes and subcodes were integrated into core categories or main themes, derived from the topics of the interview guide based on the SUS and USE questionnaires, and the broader literature on behavior change [40,41,43]. The coding was carried out by one researcher (JH), who discussed and agreed on the themes and codes with a second researcher (LtL). They discussed their findings with the research team to ensure reliability of coding and data interpretation. The transcripts were analyzed with MAXQDA version 11 (VERBI GmbH).

Quantitative Evaluation

All quantitative data were analyzed with IBM SPSS software (Version 26). Pre and postintervention changes were compared using a paired-sample *t* test. Normality assumptions were checked with the Kolmogorov-Smirnov test. If normality was violated, a Wilcoxon signed-rank test was performed. Significance was accepted at $P<.05$. Effect sizes were determined by Hedges g, except when assumptions were violated and the effect size was determined by $z/(\sqrt{n})$ [63]. Effect sizes can be interpreted based on the following: $g<0.2$ indicates a very small effect size, $g=0.2$-0.5 indicates a small effect size, $g=0.5$-0.8 indicates a medium effect size, and $g>0.8$ indicates a large effect size.

Results

Participants

Twenty-one participants were included in the process and effect evaluation study, 11 of whom completed all pre- and postmeasurements during the intervention period, as shown in Figure 3. One participant completed only the interview at the postmeasurement, and two participants did not complete the nutritional diaries and questionnaires at the postmeasurement. Demographic information of the participants who completed the intervention period are summarized in Table 1. No significant differences in demographic characteristics were found between the remote-guided and stand-alone groups. Because of the small group sizes, the results of the total population are presented. The results of statistical comparisons within the remote-guided and stand-alone groups are presented in Supplementary Appendix 3.

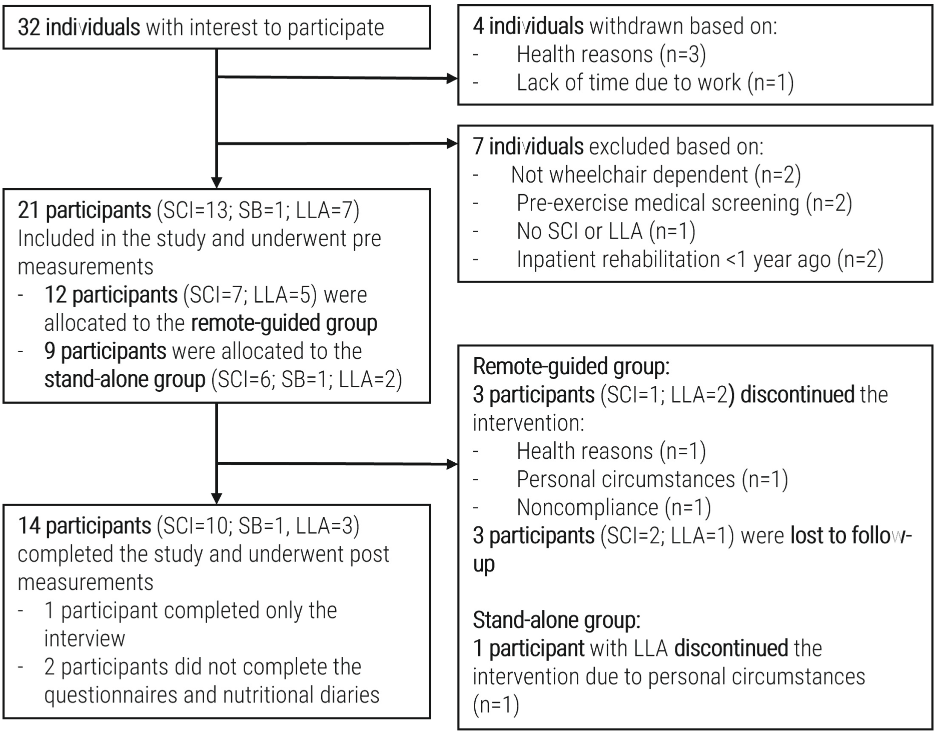


Figure 3. Flow chart of the participant inclusion. LLA: lower limb amputation; SB: spina bifida; SCI: spinal cord injury.

Table 1. Demographic characteristics of the participants.

Characteristics	Baseline (N=21)	Participants that completed the postintervention interview		
		Remote-guided (n=6)	**Stand-alone (n=8)**	**Total group (n=14)**
Gender (female/male), n	14/7	4/2	5/3	9/5
Spinal cord injury, n				
Total	14	4	7	11
Tetraplegic	1	0	1	1
Paraplegic	13	4	6	10
Lower limb amputation, n				
Total	7	2	1	3
Unilateral	4	2	0	2
Bilateral	3	0	1	1
Age (years), mean (SD)	51.6 (11.9)	55.5 (11.7)	54.1 (11.8)	54.7 (11.3)
Height (m), mean (SD)	1.68 (0.20)	1.74 (0.11)	1.64 (0.24)	1.69 (0.20)
Body mass (kg), mean (SD)	87.6 (21.5)	88.7 (19.8)	80.1 (19.4)	83.8 (19.3)
BMI (kg/m^2), mean (SD)	33.7 (13.1)	30.0 (5.9)	31.6 (11.5)	30.9 (9.2)
Time since injury (years), mean (SD)	15.5 (15.8)	10.7 (6.3)	22.1 (22.5)	17.2 (17.8)

Qualitative Evaluation

Prior Experience

Most participants (n=11) indicated they were reasonably to very experienced smartphone app users. Three participants did not consider themselves experienced with smartphones, including one participant who indicated that they mainly use a tablet, which was also used to run the WHEELS app. Six participants had no experience, two had minimal experience, and six had more extensive experience with lifestyle apps prior to participation in this study.

Themes

Overview

The codes and subcodes that emerged from the content analysis could be clearly classified under the dimensions of usability and feasibility of interest for this study. Therefore, the topics of the interview guide largely corresponded to the main themes used to categorize the results: (1) motivation and lifestyle goals, (2) app use and adherence, (3) satisfaction, (4) usefulness, (5) ease of learning, (6) ease of use, and (7) needs and suggestions for improvement. The themes were gathered and presented together for the app in general, and for the specific physical activity and exercise, food, sleep and relaxation, and community sections of the app.

Motivation and Lifestyle Goals

Motivations mentioned to participate in the pilot study were incentive to work on a healthy lifestyle, gaining insight into/becoming aware of physical activity and nutritional behavior, discovering new exercises, critically testing the app, and making suggestions for improvement. Participants mentioned at least one goal they hoped to achieve with support of the app. Ten of the 14 participants indicated weight loss as a lifestyle goal, 8 participants had goals related to increasing physical activity/exercise, 4 indicated healthy energy and/or food intake as lifestyle, 3 mentioned more overarching goals such as staying or becoming healthy and fit, and one participant indicated that he had a goal related to rest and relaxation, which was to fall asleep better.

> *Well, what I said: on the one hand to maintain fitness and also to maintain weight, because with age, weight goes on rather than it goes off. Especially when you sit all day, it is more difficult than when you walk, I think. So I would rather keep that stable and yes, in the positive case, I could also lose some weight. [Participant 5, female, 59 years old, LLA]*

Ten participants reported having partially achieved one or more lifestyle goals, five of whom indicated that they had lost weight. "And yes the food, I was very busy with losing weight. I succeeded, so it works well in that respect." [Participant 9, female, 42 years old, SCI]

Different reasons were mentioned for why lifestyle goals were not (or only partially) achieved, such as bad weather (cold and wet); hay fever; personal circumstances, including the death of a loved one; laxity; stubbornness; shoulder injury; or having set too ambitious goals. Additionally, the goal of improving falling asleep was difficult to target specifically. "I wanted to lose 5 kilos and in the period I was working on this I already realized that this was a bridge too far." [Participant 4, male, 67 years old, SCI]

Partially achieving the lifestyle goals was not always entirely attributed to use of the app. Some participants indicated that participating in the pilot study, and therefore consciously working on a healthy lifestyle, already provided sufficient incentive to pursue existing lifestyle goals. Nevertheless, the majority indicated that the app had influenced their physical activity and dietary behavior, particularly contributing to raising awareness of, and providing insight into, daily energy and nutrient intake.

> *Because normally, when there are some things on the table you really have no idea how many calories are in it. And if you look a little further in the app, you can also see how many carbohydrates and other macronutrients are in it. So it was firstly to build up a bit of discipline:*

what will I shove in during the day. And secondary, a piece of awareness was built up. Then you have eaten a nice pizza, and suddenly get 1200 calories on your plate, and then you are not allowed to eat anything for the rest of the day. [Participant 1, male, 64 years old, SCI]

In addition, the participants explained that the app provided incentive discipline to exercise regularly and to eat healthy, with pop-up reminders to exercise contributing to this.

I thought I should honestly fill in what I eat and drink and then you see your own overview… Then [when the overview shows a surplus in calories] you think: another day tomorrow, I have to fix this right away. [Participant 17, female, 57 years old, SCI]

I definitely do less now without the app. Because the app sort of said: now it's time for your weekly gym exercise. [Participant 19, male, 39 years old, SCI]

Finally, it was mentioned that the app provided direction and tools to adopt a healthy lifestyle, such as by offering exercises.

Look, I sit in a wheelchair and I don't do anything else. But now you see oh, I can do that and I can do that and I can do that… And now I have come this far, also together with my physiotherapist, that I get out of that wheelchair. That I look at what kind of standing exercises and suchlike I could do, and that motivates me enormously. [Participant 16, female, 70 years old, LLA]

Application Use and Adherence

Six participants reported having used the app daily, two had used the app extensively during the 12-week intervention period, but not daily, whereas five had used the app only in the beginning (2-5 weeks), and one had used the app irregularly. Three reasons were given by several participants for having used (certain parts of) the app less or not at all. The first reason was dissatisfaction with the functioning or ease of use of the app: "If at some point you feel that it is not working in the way you would like, yes, then you think forget it." [Participant 1]

The second reason was personal circumstances such as an injury, illness, and psychological stress: "I have also seen the cardio program. There was something about building up biking, but just because I was not in good shape, I didn't start doing that." [Participant 2, female, 64 years old, SCI]

The third reason given was laziness:

> *I did not use that [food part]*
> *Interviewer: Okay and what was the reason for that?*
> *Yes, laxity, ease. Maybe also the stubbornness that you think: yes, I know how to lose weight. Participant 11, male, 61 years old, SCI]*

The food diary was used most intensively, which was completed almost daily by six participants. Four others also used the food part but less intensively or quit after a few weeks. Another participant only tested the food part for usability.

Four participants used the exercise database and preprogrammed exercise routines daily or frequently during the 12 weeks. One participant also used these parts of the app regularly, although less frequently. Four participants used the physical activity and exercise part in the beginning but stopped after a few weeks. In addition, one participant had only explored the exercise database and training programs and another participant only tested the

physical activity and exercise part for usability. Competitive activities were mentioned as one of the reasons for no or little use of the exercise part: “In the beginning I also used the app, but because I went to the gym twice a week, I stopped using it.” [Participant 2]

A second reason given to stop using the exercise part was that the app was no longer needed because the exercises were known and could be performed without the app.

> *Yes, those were just example exercises and then I thought: oh yes, that is a fun one, oh I am going to do that, and: oh, that is also a fun one that I am going to do and then you have four or five [exercises]. Yes, then I really don’t need that app anymore. Because then I already know what to do. Then I no longer have to look at that app every day. [Participant 5]*

Three participants had used the sleep and relaxation part. The first participant performed the relaxation exercises several times, the second had read the information about sleep and relaxation, and the third explained that he still used the tips to relax because he slept rather poorly and the tips helped him to relax. A fourth participant only tested the sleep and relaxation part for usability. A frequently mentioned reason for why the sleep and relaxation part had not been used was that it was not needed because participants did not experience stress or sleeping problems: “Not looked at [sleep and relaxation part] because I am sufficiently balanced and relaxed.” [Participant 11]

Three participants used the informative community groups. They were alerted by email to new messages in which lifestyle information and tips were shared and read them. The interactive part of the community in which participants could ask each other questions, and share experiences and tips was hardly used. One participant expressed that it was unfortunate that hardly any interaction had started. Reasons given for not being active in the community were unwillingness to brag and incomparability.

> *It is more because it is so incomparable to each other. Look, someone who just got out of rehabilitation may be very proud to have handcycled 10 kilometers. While I think, yes, when I say I have done 20 kilometers... I think that...I don't feel the need to proclaim it or anything. I think, yes, you are not comparable. [Participant 5]*

Finally, the calendar was used by several participants to plan their exercises. Two participants reported having used the progress registration part by regularly registering their weight and WC. A few participants started the handcycling challenge; however, no participant completed this challenge because it was unclear how the time that was handcycled for this challenge could be recorded.

Satisfaction

Overall, participants were satisfied with the WHEELS app. Several participants indicated that they wanted to continue using the app. It was further noted they were happy that there is finally a lifestyle app suitable for wheelchair users, that the combination of attention to healthy nutrition and physical activity/exercise is nice, and that the app has something in it for everyone.

> *I think that because you have a lot of different things in it, you have a very large target group. Some things may not be helpful to me, but that's not to say it's not useful for the app. [Participant 9]*

When asked if they would recommend the app to others, 12 participants answered yes, one participant would only recommend the food part, and one person would not recommend the app at all: "Maybe, I haven't thought about it. But there is, yeah, it's a good way to start up. Until you get into a routine." [Participant 19]

With regard to the exercise database and preprogrammed exercise routines, the participants indicated that there was great variation in exercises and that the animation provided a clear example of the desired implementation: "I have to tell you, I think it looks super cool. Also the exercises that are offered, I think the variation in exercises is very good." [Participant 11]

Some participants were less satisfied with the exercise database because they had difficulty finding the right exercises: "And then you see so many exercises in that list that you actually do not know which one to choose. And that was a problem for me." [Participant 7, male, 54 years old, SCI]

Regarding the food part, the participants indicated that they liked that that the app provided insight into their daily energy and nutrient intake. Furthermore, they explained that the food product list was very extensive, as almost every food could be found in the list and then easily added to the food diary.

> *I found the food diary very useful, you can see exactly what you eat in calories and protein. [Participant 8, female, 34 years old, SCI]*

> *The nice thing about the food app is that no matter what you eat or drink, you can always find it somewhere and it has a calorie number.* [Participant 1]

The relaxation part was rarely used, making it difficult to indicate whether the participants were satisfied with the content. Two participants indicated that the exercises were perhaps a bit too spiritual: "Well it often comes across as very spiritual, so to speak, while, yes, while that might raise an aversion." [Participant 9]

With regard to the community aspect, a few participants stated that it was motivating that lifestyle tips were regularly posted. Opinions were divided about the community group in which experiences and questions could be shared: some considered this to be of added value, whereas others did not feel the need for it.

Usefulness

The participants indicated that the app is particularly useful for (recent) wheelchair users who have little physical activity and exercise experience, providing tools and inspiration to start exercising and develop a healthy lifestyle.

> *Because I see a lot of wheelchair users around me who are simply aimless. Who can have a huge hold on that [the app]. Especially if you are not physically active or are starting to be physically active.* [Participant 11]

More experienced wheelchair users with a more physically active lifestyle had less need for the complete app, but found some parts useful, in most cases concerning the food part to gain insight into dietary intake, as described in the previous section on satisfaction.

Ease of Learning

Opinions differed on how easy it was to learn how to use the app. Some participants quickly became skillful, others needed a few weeks, and still others gave up using the exercise part because they could not learn to work with it quickly. Most interviews showed that learning to work with the app takes some time, and not all participants had the patience and will to spend time on this.

> *The first period is quite a lot of investing and maybe I could have got a bit more out of it. But then you expect all users to use it, invest and maybe benefit from it afterward, and I think that is too much to ask. [Participant 17]*

Some participants indicated they could not repeat actions they had previously performed with the app, such as scheduling an exercise in the calendar. This indicates it was not easy for all participants to remember how to use the app. Some participants also indicated they had asked family members to help them learn to work with the app. This also reveals that learning to work with the app was not experienced as easy by all participants.

> *Actually during the first 2 or 3 weeks of use, you don't know all the tips at once, because that is too much, but then the advantage is that my daughter is very handy and serious with that [app use]. So then I got another tip and I could do a bit more. Yes, perfect that app." [Participant 12, female, 61 years old, LLA]*

The part that participants most often reported as unsuccessful or difficult to master was putting together a training schedule themselves.

> *Well, what I said earlier about making such a [exercise] program of your own and then...Yes that. I could not completely figure that out, and I must honestly say that at some point I also think: well, never mind. [Participant 5]*

Finally, the participants hardly reported any problems with learning to work with the food part. This part seemed to work quite intuitively.

Ease of Use

The participants generally found the food part easier to use than the exercise part. The vast majority labeled the food part as easy to use, whereas the exercise part was described as easy to use by about half of the participants.

Three factors emerged that negatively affected the ease of use of the exercise part. Not all participants were well aware of the distinction and coherence between the exercise database with which personal training routines could be compiled, the preprogrammed exercise routines, and the calendar.

> *Well with those exercise programs I found it a bit vague at first because you also have two boxes [tiles at the start screen that direct to the different parts of the app] with exercise or something. [Participant 8]*

Second, the participants indicated they had difficulty finding suitable exercises in the exercise database. Several participants were unaware of the possibility or did not know how to use the search box to find specific exercises.

> *For example, if I had done something new at the physio, it was sometimes a bit of a search in that whole list of: What suits this best? And then indeed there were sometimes whole laundry lists with exercises in it…I think that at some point it just missed its target…[Participant 4]*

Third, it was not clear to all participants how activities could be registered to end up in the activity diary or the activity stream.

> *And for example I had put an exercise in the calendar and then I thought oh then it will automatically register that I did that, but that is not the case. Then you had to click that again. [Participant 8]*

The participants generally found the food part clear to use. Several participants indicated that they liked the fact that the food product list was so extensive that it was easy to log consumed products in the food diary: "Yes, I actually did not come across a product that I could not find [in the food product list]." [Participant 14]

The participants found the time it took to keep a food diary less user-friendly. Several participants were not aware of the possibility to save frequently eaten meals such as a fixed breakfast. This means that the individual products that make up the meal only need to be entered once. The next time, the entire meal can be added to the food diary with one click. Partly because participants were not aware of this possibility, they indicated that they were tired of having to import the same products every time.

> *At some point you are a bit done with reentering those foods every time. I always eat a bowl of curd with muesli in the morning. Yes, the next day I had to scan it again or had to go back and find out where that curd is. And I thought that was a bit of a disadvantage. [Participant 7]*

Needs and Suggestions for Improvement

The participants expressed several needs and suggestions for improvement that were largely related to the difficulties they experienced during app use. The most frequently mentioned needs and suggestions related to personalization, user instruction or remote guidance, and improving insight into energy expenditure by connecting a wrist-worn activity monitor to the app. No difference in suggestions was found between the remote-guided and stand-alone groups.

In the exercise part, better personalization could make it easier to find and select suitable exercises. In addition, it was suggested that the preprogrammed exercise routines could be better tailored to the individual needs and functional capabilities: “However, I would appreciate the programs to be a little bit more distinct to your abilities. That would have been perfect.” [Participant 19]

With regard to the food part, the participants expressed their need for personalized daily energy intake advice: “If you want to use it for people with a spinal cord injury, you really have to adjust the calorie advice, because we are actually allowed to consume fewer calories.” [Participant 7]

The user instruction was not found and used by all participants. Some participants indicated they needed a help desk for questions and problems with using the app.

> *That I couldn’t find back what I had done before was the most frustrating…That I didn’t know how I had done it before and why I couldn’t find it again…Someone who offered me guidance, by phone or every 2 weeks face-to-face, could have definitely helped me. [Participant 17])*

In addition, several participants would have liked to have had a coach to help them on their way, have questions answered, and discuss suitable activities and progress on their goals. One of the participants who had received remote guidance explained that it had been of little added value to her because the coach barely reflected on what she had done. She would have liked the coach to monitor her and to discuss progress on her goals with her: “Yes someone who says: you went over your [calorie] goal all week. Do you have an idea how you will solve this in the coming week?” [Participant 14, female, 42 years old, SCI]

Finally, it was revealed that, in combination with lifestyle guidance by a coach, the app would probably have been used more intensively: "I think I would have used it under supervision more, the WHEELS app." [Participant 17]

As a third and last suggestion, several participants explained that they would like to have better insight into their rate of exertion and energy expenditure during activities. Connecting an activity monitor for wheelchair users to the app has been suggested as an opportunity to meet this need.

> *Yes, a pedometer too, for a wheelchair user. It is nice to know what your muscles have done, what your heart rate has been and how many calories or energy you have consumed…I would rather put on a wristband for that and will also enter some extra information. [Participant 17]*

Quantitative Evaluation

Usability and Feasibility

The average SUS score for all participants was 58.6, which is below the general average interface SUS score of 70 [44]. Participants showed little difference in scores between the remote-guided and stand-alone groups in SUS score and USE dimension scores. All SUS scores and USE dimensions scores can be found in Table 2 for each group and all participants.

Table 2. Descriptive statistics of usability and feasibility questionnaires.

Questionnaire	Remote-guided (n=4)		Stand-alone (n=7)		All (N=11)	
	Mean (SD)	**Range[a]**	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**
System Usability Scale	56.0 (5.8)	14.0	60.1 (32.2)	84.0	58.6 (25.2)	84.0
Ease of use	5.0 (1.7)	4.3	5.6 (3.8)	9.7	5.4 (3.1)	9.7
Satisfaction	5.1 (2.2)	4.8	5.2 (3.7)	9.7	5.2 (3.1)	9.7
Ease of learning	5.5 (3.2)	7.0	6.1 (4.2)	9.5	5.9 (3.7)	9.5

[a]Represents the spread; the difference between the maximum and minimum values.

Nutritional Intake

Nutritional intake changes of 10 participants over the 12-week intervention period are shown in Table 3. The quality of the diet records of two participants was not adequate (ie, portion size or ingredients used were not described in sufficient detail to obtain macronutrients correctly) to analyze at least 2 recorded days at pre and postmeasurement, and these records were therefore excluded. No significant differences were found over time within the whole group, or within the remote-guided or stand-alone groups separately, in total calorie count or macronutrients. However, there was a positive trend (with medium effect sizes) toward a reduction in fat consumed and relative alcohol intake. Other outcomes showed either small or very small effect sizes. Full results of the separate groups are presented in Table S1 in Supplementary Appendix 3.

Table 3. Nutritional intake pre and post 12-week intervention based on diet records (n=10).

Daily average consumed	Pre, mean (SD)	Post, mean (SD)	P value	Effect size
Kilocalories	1920 (531)	1637 (377)	.14[a]	0.46
Protein (g)	79.8 (21.8)	74.1 (13.5)	.37	0.28
Fat (g)	82.9 (31.4)	69.6 (22.9)	.07[a]	0.56
Carbohydrates (g)	179.8 (61.3)	154.7 (63.3)	.24[a]	0.37
Alcohol (g)	12.7 (13.3)	7.9 (10.7)	.16[a]	0.44
Protein (%)	16.9 (3.7)	18.6 (3.6)	.14[a]	0.47
Fat (%)	38.4 (8.5)	38.2 (8.6)	.88	0.05
Carbohydrates (%)	37.7 (8.1)	37.3 (10.3)	.88[a]	0.05
Alcohol (%)	4.5 (4.7)	3.4 (5.0)	.09[a]	0.53

[a] Non-parametric test used due to violation of normality with corresponding effect size.

Body Composition

For the whole group, all body composition outcomes showed favorable changes over the intervention period, which was significant for WC, fat mass percent, fat-free mass, and fat-free mass percent, and a trend toward significance for body mass and BMI (Table 4). Large effect sizes were found for fat mass percent and fat-free mass percent, whereas all other outcomes showed medium effect sizes except for body mass. Results for each group separately are shown in Table S2 in Supplementary Appendix 3, demonstrating slightly better results in favor of the remote-guided group compared to the stand-alone group.

Table 4. Body composition changes pre and post the 12-week intervention (n=13).

Body composition	Pre, mean (SD)	Post, mean (SD)	P value[a]	Effect size
Body mass (kg)	83.0 (20.0)	81.6 (20.6)	.09	0.49
BMI (kg/m^2)	29.7 (7.8)	29.1 (7.8)	.07	0.53
WC[b] (cm)	103.9 (13.5)	101.4 (13.8)	.02	0.76
FM[c] (kg)	32.1 (10.1)	26.7 (9.2)	.004	0.96
FM (%)	39.2 (9.5)	33.4 (10.5)	.004	0.97
FFM[d] (kg)	50.9 (15.4)	54.9 (17.7)	.02	0.70
FFM (%)	60.8 (9.5)	66.6 (10.5)	.004	0.97

[a]Paired-sample *t* test.
[b]WC: waist circumference.
[c]FM: fat mass.
[d]FFM: fat-free mass.

Questionnaire Outcomes

No significant changes in questionnaire outcomes were found over time (Table 5), although the PSQI results showed a favorable trend toward better sleep quality. A medium effect size was found in sleep quality. Small effect sizes were found on the CIS20R and four subcategories of the SF-36E. No clear differences were found between groups, as shown in Table S3 in Supplementary Appendix 3.

Table 5. Results from questionnaires pre and post the 12-week intervention (n=12).

Questionnaire	Pre, mean (SD)	Post, mean (SD)	P value	Effect size
PASIPD[a] (MET h/day	23.8 (15.1)	22.4 (12.2)	.64	0.14
GSES[b]	34.1 (4.3)	33.6 (4.2)	.69	0.11
ESES[c]	33.0 (3.8)	32.4 (4.4)	.50[d]	0.07
CIS20R[e]	72.3 (11.6)	69.6 (7.7)	.18[d]	0.39
PSQI[f]	8.0 (2.7)	6.7 (2.2)	.063	0.57
SF-36E[g]				
Physical functioning	52.1 (18.6)	49.2 (18.2)	.58	0.16
Social functioning	72.9 (17.5)	79.2 (20.9)	.36[d]	0.27
Role limitation physical	57.8 (26.1)	59.4 (18.0)	.84	0.06
Role limitation emotional	79.2 (23.7)	74.3 (24.7)	.53[d]	0.18
Mental health	81.7 (12.6)	74.6 (15.1)	.13	0.46
Energy/vitality	62.5 (14.6)	62.5 (12.2)	>.99	<0.01
Pain	59.0 (17.6)	49.1 (21.5)	.11	0.48
General health perceptions	63.8 (18.1)	60.0 (21.3)	.37[d]	0.26

[a]PASIPD: Physical Activity Scale for individuals with Physical Disability.
[b]GSES: General Self-Efficacy Scale.
[c]ESES: Exercise Self-Efficacy Score.
[d]Nonparametric test used due to violation of normality.
[e]CIS20R: Checklist Individual Strength.
[f]PSQI: Pittsburgh Sleep Quality Index.
[g]SF-36E: Short-Form Health Survey 36 Enabled.

Discussion

Principal findings

This paper describes the development of the WHEELS mHealth app for wheelchair users with SCI or LLA. Additionally, the first insight on usability, feasibility, and effectiveness of the app is provided. The perceived usability and feasibility varied among participants and showed room for improvement. Participants did show a positive development in body composition such as a significant decrease in fat mass, which was often mentioned as a personal lifestyle goal. Combined with a positive trend for sleep quality, and reduced fat and alcohol intake, the app seems promising to improve lifestyle behavior in wheelchair users, with the caveat that no change in physical activity levels were detected. Environmental barriers might have contributed to this, which cannot be influenced by mHealth.

The SUS score and usability scores for ease of use, ease of learning, and satisfaction ranged between the minimal (0) and maximal (10) scores, indicating a varied user experience. The questionnaire outcomes were in line with the interviews, in which some participants were merely positive and experienced no struggle using the app, whereas others mentioned difficulties using the exercise and planning part, for example. These differences in perceived usability could be related to differences in motivation and time spent within the app, and likely influenced the extent to which the app has led to the desired lifestyle behaviors. This is best explained by the Fogg behavior model, which describes that behavior change is related to three elements, motivation, ability, and trigger, where motivation and ability show an inverse relationship [64]. If a certain level of effort and time (motivation) was not put into understanding the app (ability), an individual would not meet the minimal requirements to benefit from the app. Participants who were willing to put more time and effort in becoming familiar with the app, and thus showed more motivation, were more positive about the product and expressed fewer difficulties working with the exercise and planning part. This is in line with earlier research, which shows that a higher level of app engagement is associated with increased intervention effectiveness [65–67]. However, this could also be a flaw of the app, as the required ability might be too high to fully benefit from the app. Therefore, by reducing the ability needed to understand the app, less motivation is needed to continue using the app. Clearer and easier instructions that require little time and effort could possibly reduce the required motivation to meet the ability needed to benefit working with the app.

Another solution for overcoming difficulties with using the app could be found in a remote-guided intervention approach, in which the app is combined with guidance by a lifestyle coach. A remote-guided approach seems to be more promising in achieving improvement in behavioral and health outcomes [25]. Unfortunately, from this study, no conclusions can be drawn regarding differences between those who used the app as a stand-alone intervention and those who used the app with remote guidance. The remote-guided group did show more significant changes than the stand-alone group; however, owing to a larger dropout than expected, the group sizes were small and thus results should be interpreted with caution. Half of the participants were allocated to a remote-guidance group where they received regular phone consultations by students in Functional Exercise Therapy. However, based on interview reports, the effect of the provided phone consultations was limited, possibly due to the lack of experience the students had in motivational interviewing. Previous research suggests more advanced and prolonged training in motivational interviewing is needed to allow embedding of these skills [68]. Another explanation for the limited effect is that nonverbal communication was hardly possible because most consultations took place by phone, which could have reduced the consultation effects due to loss of possible valuable cues and information [69]. Moreover, multiple participants from the stand-alone group indicated that a consultant would have benefitted them in either solving difficulties in working with the app or as an additional motivator and guide in behavior change. The addition of peer health coaches could be of added value, as research shows that individuals with SCI can benefit from this type of support [70]. Therefore, it would be interesting to investigate the effect of using the app in combination with face-to-face guidance of trained peer health coaches (blended).

When taking a closer look at the effect evaluation, significant and favorable changes were seen in measures of body composition. This seems to be in line with other findings such as reduced body mass, reduced fat intake, and reduced relative alcohol intake, although these reductions were not statistically significant. Registered body composition changes were most likely partly caused by nutritional changes. The feature to track nutrition intake raised the participants' awareness of their nutritional intake and triggered them to change dietary habits, which was also mentioned during the interviews. The diet records showed a trend toward a positive change in nutrition behavior. These changes were not statistically significant, possibly due to the small sample size. No changes in physical activity levels were found, which could be caused by factors at the interpersonal, institutional, community, and policy influence levels that were not targeted in the app but are associated with physical activity among wheelchair users [71]. However, the significant increase in fat-free mass would suggest an increase in muscle mass caused by physical activity. Moreover, physical activity was measured with a self-reported questionnaire, which correlates poorly with objective physical activity outcomes in participants who were already relatively active at the start of the study [72]. Therefore, there may have been an increase in physical training that was not reflected in the total PASIPD score.

Limitations and Strengths

The targeted groups, wheelchair users with SCI and LLA, may experience different barriers and facilitators for developing a healthy lifestyle, and when developing the app we expected that the app had to be tailored accordingly. However, the needs assessment showed many similarities, resulting in the use of similar behavior change techniques for both groups. The intention was to use the 16 change strategies in the intervention to influence the main behavioral determinants identified in the development phase. However, it is uncertain whether all 16 strategies were applied as intended during the study. For example, tailoring options were limited due to software limitations, and several participants had not used all parts of the app with the result that they were not exposed to all behavior change strategies. This could have possibly affected the usability and effectiveness outcomes.

The interview yielded suggestions for improvement that could in turn improve the usability, feasibility, and effectiveness of the app. However, owing to high dropout, relevant feedback may have been missed from users who were less satisfied with the intervention or had more difficulty changing their behavior. Unfortunately, in most cases, we were unable to determine the reason for dropout, as this could have provided valuable information. The relative high dropout rate led to a lower sample size than intended and a possible biased user experience. Additionally, this resulted in only one individual with tetraplegia completing the study, making these results less generalizable to the whole SCI community. Nevertheless, despite the low inclusion rate, significant positive changes in body composition were found, which is very promising. However, these results should be interpreted with caution, as a higher possibility of type II errors is present due to the small sample size and multiple performed tests.

Several body composition outcomes were measured with a BIA device. The transformation formula used to calculate measured resistance to body composition outcomes was based on empirical data from the general population. Thus, the validity of the BIA measurements on this specific population could be argued. However, systematic deviation does not have to affect test-retest reliability, which would therefore make the BIA still able to detect changes over time. Additionally, the BIA outcomes seem to be in line with interview outcomes and nutrition diaries. Physical activity levels did not show any changes, which was subjectively measured with the PASIPD questionnaire and, as mentioned above, correlates poorly with objective physical activity outcomes that represent physical activity more accurately [72].

Future Studies

These first results on effectiveness of the WHEELS app seem to be promising for body composition changes, nutritional habits, and sleep quality. Improvements in manual instructions and support regarding use of the app are suggested. A study with a larger sample size and stronger research design, for example a repeated-measures mixed model design, is warranted, which would allow further investigation on the effectiveness of the different parts of the app for improving body composition, dietary behavior, physical activity, and health, and the interaction between stand-alone and remote-guided use of the intervention. In this larger study, it is recommended to measure physical activity objectively (eg, with accelerometry) to be able to conclude whether the app does or does not influence physical activity behavior. Preferably, such a study should be performed in participants who are less active at inclusion compared to the participants of this study. Accelerometry, including heart rate, would be recommended, as it could differentiate among intensity levels and thus provide a more valid physical activity outcome.

Conclusion

This paper describes the development, usability, and feasibility of the WHEELS mHealth app for wheelchair users with SCI or LLA, and provides the first insight into its effectiveness. Although usability could be improved, the app scored reasonably well and seems to be feasible to implement on a larger scale. First results on lifestyle changes seem promising, and effectiveness could possibly increase if the mentioned suggestions for improvement by participants are processed into the app.

Acknowledgements
This research is co-financed by the National Taskforce for Applied Research SIA, part of the Netherlands Organisation for Scientific Research (NWO), under grant RAAK.PUB03.029. The members of the WHEELS Study Group are:

LE van den Akker, L Alpay, H Bijwaard, M Deutekom, R Doms, JFM Holla (program coordination): Inholland University of Applied Sciences, Haarlem, The Netherlands.
T Dadema, JM Dallinga, S Dankers, RH Engelbert, M Tieland, B Visser, PJM Weijs: Amsterdam University of Applied Sciences, Amsterdam, The Netherlands.
S de Groot, TWJ Janssen: Amsterdam Rehabilitation Research Centre, Reade, Amsterdam, The Netherlands.
H Houdijk, LJ Valent: Heliomare Rehabilitation Centre, Wijk aan Zee, The Netherlands.
LHV van der Woude: University Medical Centre Groningen, Groningen, The Netherlands.
JBJ Bussmann: Erasmus University Medical Centre, Rotterdam, The Netherlands.
N van Schijndel: Virtuagym B.V., Amsterdam, The Netherlands.

Conflicts of interests
None declared; the involved researchers were distinct from the app developer Virtuagym B.V.

Supplementary appendixes

Supplementary appendix 1: Development process of the WHEELS app.
Supplementary appendix 2: Interview guide for the usability and feasibility study of the WHEELS project.
Supplementary appendix 3: Tables S1-S3.

References

1. Kumar K. Importance of healthy life style in healthy living. Juniper Online J Public Health 2017;2(5):11 [doi: 10.19080/jojph.2017.02.555596]
2. Pisinger C, Toft U, Aadahl M, Glümer C, Jørgensen T. The relationship between lifestyle and self-reported health in a general population: the Inter99 study. Prev Med 2009 Nov;49(5):418-423. [doi: 0.1016/j.ypmed.2009.08.011] [Medline:19716843]
3. Pell JP, Donnan PT, Fowkes FG, Ruckley CV. Quality of life following lower limb amputation for peripheral arterial disease. Eur J Vasc Surg 1993 Jul;7(4):448-451. [doi:10.1016/s0950-821x(05)80265-8] [Medline:8359304]
4. van den Berg-Emons RJ, Bussmann JB, Stam HJ. Accelerometry-based activity spectrum in persons with chronic physical conditions. Arch Phys Med Rehabil 2010 Dec;91(12):1856-1861. [doi: 10.1016/j.apmr.2010.08.018] [Medline:21112426]
5. van Langeveld SA, Post MW, van Asbeck FW, Gregory M, Halvorsen A, Rijken H, et al. Comparing content of therapy for people with a spinal cord injury in postacute inpatient rehabilitation in Australia, Norway, and The Netherlands. Phys Ther 2011 Feb;91(2):210-224. [doi:10.2522/ptj.20090417] [Medline:21212372]
6. Bragaru M, Dekker R, Geertzen JHB, Dijkstra PU. Amputees and sports: a systematic review. Sports Med 2011 Sep;41(9):721-740. [doi:10.2165/11590420-000000000-00000] [Medline:21846162]
7. Martin Ginis KA, van der Scheer JW, Latimer-Cheung AE, Barrow A, Bourne C, Carruthers P, et al. Evidence-based scientific exercise guidelines for adults with spinal cord injury: an update and a new guideline. Spinal Cord 2018 Apr;56(4):308-321. [doi:10.1038/s41393-017-0017-3] [Medline: 29070812]
8. Adriaansen J, Ruijs L, van Koppenhagen CF, van Asbeck FWA, Snoek G, van Kuppevelt D, et al. Secondary health conditions and quality of life in persons living with spinal cord injury for at least ten years. J Rehabil Med 2016 Nov;48(10):853-860 [doi:10.2340/16501977-2166] [Medline:27834436]
9. Myers J, Lee M, Kiratli J. Cardiovascular disease in spinal cord injury: an overview of prevalence, risk, evaluation, and management. Am J Phys Med Rehabil 2007 Feb;86(2):142-152. [doi: 10.1097/PHM.0b013e31802f0247] [Medline:17251696]
10. Adriaansen JJE, van Asbeck FWA, Lindeman E, van der Woude LHV, de Groot S, Post MWM. Secondary health conditions in persons with a spinal cord injury for at least 10 years: design of a comprehensive long-term cross-sectional study. Disabil Rehabil 2013 Jun;35(13):1104-1110. [doi: 10.3109/09638288.2012.712196] [Medline:22991949]
11. Boulos MNK, Wheeler S, Tavares C, Jones R. How smartphones are changing the face of mobile and participatory healthcare: an overview, with example from eCAALYX. Biomed Eng Online 2011 Apr;10:24 [doi:10.1186/1475-925X-10-24] [Medline:21466669]
12. van den Berg-Emons RJ, Bussmann JB, Haisma JA, Sluis TA, van der Woude LH, Bergen MP, et al. A prospective study on physical activity levels after spinal cord injury during inpatient rehabilitation and the year after discharge. Arch Phys Med Rehabil 2008 Nov;89(11):2094-2101. [doi: 10.1016/j.apmr.2008.04.024] [Medline:18996237]
13. Haisma JA, Bussmann JB, Stam HJ, Sluis TA, Bergen MP, Dallmeijer AJ, et al. Changes in physical capacity during and after inpatient rehabilitation in subjects with a spinal cord injury. Arch Phys Med Rehabil 2006 Jun;87(6):741-748. [doi:10.1016/j.apmr.2006.02.032] [Medline:16731207]

14. Desveaux L, Goldstein RS, Mathur S, Hassan A, Devlin M, Pauley T, et al. Physical Activity in Adults with Diabetes Following Prosthetic Rehabilitation. Can J Diabetes 2016 Aug;40(4):336-341. [doi: 10.1016/j.jcjd.2016.02.003] [Medline:27052673]

15. Farkas GJ, Pitot MA, Berg AS, Gater DR. Nutritional status in chronic spinal cord injury: a systematic review and meta-analysis. Spinal Cord 2019 Jan;57(1):3-17. [doi:10.1038/s41393-018-0218-4] [Medline: 30420688]

16. Westerkamp EA, Strike SC, Patterson M. Dietary intakes and prevalence of overweight/obesity in male non-dysvascular lower limb amputees. Prosthet Orthot Int 2019 Jun;43(3):284-292. [doi: 10.1177/0309364618823118] [Medline:30663528]

17. van den Akker LE, Holla JFM, Dadema T, Visser B, Valent LJ, de Groot S, WHEELS-study group. Determinants of physical activity in wheelchair users with spinal cord injury or lower limb amputation: perspectives of rehabilitation professionals and wheelchair users. Disabil Rehabil 2020 Jul;42(14):1934-1941. [doi: 10.1080/09638288.2019.1577503] [Medline: 30924706]

18. Holla JFM, van den Akker LE, Dadema T, de Groot S, Tieland M, Weijs PJM, WHEELS-study group. Determinants of dietary behaviour in wheelchair users with spinal cord injury or lower limb amputation: Perspectives of rehabilitation professionals and wheelchair users. PLoS One 2020 Jan;15(1):e0228465 [doi: 10.1371/journal.pone.0228465] [Medline: 32004359]

19. Nooijen CFJ, Stam HJ, Schoenmakers I, Sluis TAR, Post MWM, Twisk JWR, Act-Active Research Group, et al. Working mechanisms of a behavioural intervention promoting physical activity in persons with subacute spinal cord injury. J Rehabil Med 2016 Jul;48(7):583-588 [doi:10.2340/16501977-2110] [Medline:27346837]

20. Littman AJ, Haselkorn JK, Arterburn DE, Boyko EJ. Pilot randomized trial of a telephone-delivered physical activity and weight management intervention for individuals with lower extremity amputation. Disabil Health J 2019 Jan;12(1):43-50. [doi:10.1016/j.dhjo.2018.08.002] [Medline:30115584]

21. Ma JK, West CR, Martin Ginis KA. The effects of a patient and provider co-developed, behavioral physical activity intervention on physical activity, psychosocial predictors, and fitness in individuals with spinal cord injury: a randomized controlled trial. Sports Med 2019 Jul;49(7):1117-1131. [doi: 10.1007/s40279-019-01118-5] [Medline:31119717]

22. Payne HE, Lister C, West JH, Bernhardt JM. Behavioral functionality of mobile apps in health interventions: a systematic review of the literature. JMIR Mhealth Uhealth 2015 Feb;3(1):e20 [doi: 10.2196/mhealth.3335] [Medline:25803705]

23. Singh G, MacGillivray M, Mills P, Adams J, Sawatzky B, Mortenson WB. Patients' perspectives on the usability of a mobile app for self-management following spinal cord injury. J Med Syst 2019 Dec;44(1):26. [doi:10.1007/s10916-019-1487-y] [Medline:31828440]

24. Al Ayubi SU, Parmanto B, Branch R, Ding D. A persuasive and social mHealth application for physical activity: a usability and feasibility study. JMIR Mhealth Uhealth 2014 May;2(2):e25 [doi: 10.2196/mhealth.2902] [Medline:25099928]

25. Schoeppe S, Alley S, Van Lippevelde W, Bray NA, Williams SL, Duncan MJ, et al. Efficacy of interventions that use apps to improve diet, physical activity and sedentary behaviour: a systematic review. Int J Behav Nutr Phys Act 2016 Dec;13(1):127 [doi:10.1186/s12966-016-0454-y] [Medline: 27927218]

26. Webb TL, Joseph J, Yardley L, Michie S. Using the internet to promote health behavior change: a systematic review and meta-analysis of the impact of theoretical basis, use of behavior change techniques, and mode of delivery on efficacy. J Med Internet Res 2010 Feb;12(1):e4 [doi: 10.2196/jmir.1376] [Medline:20164043]

27. van Genugten L, Dusseldorp E, Webb TL, van Empelen P. Which combinations of techniques and modes of delivery in internet-based interventions effectively change health behavior? A meta-analysis. J Med Internet Res 2016 Jun;18(6):e155 [doi:10.2196/jmir.4218] [Medline:27268104]

28. van der Ploeg HP, van der Beek AJ, van der Woude LHV, van Mechelen W. Physical activity for people with a disability: a conceptual model. Sports Med 2004;34(10):639-649. [doi: 10.2165/00007256-200434100-00002] [Medline:15335241]

29. Bartholomew L, Markham C, Ruiter R, Fernandez M, Kok G, Parcel G. Planning health promotion programs: an intervention mapping approach. 4th ed. San Fransisco: Jossey-Bass; 2016.

30. Smith EM, Sakakibara BM, Miller WC. A review of factors influencing participation in social and community activities for wheelchair users. Disabil Rehabil Assist Technol 2016;11(5):361-374 [doi:10.3109/17483107.2014.989420] [Medline:25472004]

31. Bardus M, van Beurden SB, Smith JR, Abraham C. A review and content analysis of engagement, functionality, aesthetics, information quality, and change techniques in the most popular commercial apps for weight management. Int J Behav Nutr Phys Act 2016 Mar;13:35 [doi:10.1186/s12966-016-0359-9] [Medline:26964880]

32. Swift DL, Johannsen NM, Lavie CJ, Earnest CP, Church TS. The role of exercise and physical activity in weight loss and maintenance. Prog Cardiovasc Dis 2014;56(4):441-447 [doi: 10.1016/j.pcad.2013.09.012] [Medline:24438736]

33. Marshall NS, Glozier N, Grunstein RR. Is sleep duration related to obesity? A critical review of the epidemiological evidence. Sleep Med Rev 2008 Aug;12(4):289-298. [doi:10.1016/j.smrv.2008.03.001] [Medline:18485764]

34. Wu Y, Zhai L, Zhang D. Sleep duration and obesity among adults: a meta-analysis of prospective studies. Sleep Med 2014 Dec;15(12):1456-1462. [doi:10.1016/j.sleep.2014.07.018] [Medline: 25450058]

35. Chaput J. Sleeping more to improve appetite and body weight control: dream or reality? Am J Clin Nutr 2015 Jan;101(1):5-6. [doi: 10.3945/ajcn.114.101543] [Medline:25527744]

36. Rayward AT, Burton NW, Brown WJ, Holliday EG, Plotnikoff RC, Duncan MJ. Associations between changes in activity and sleep quality and duration over two years. Med Sci Sport Exerc 2018;50(12):2425-2432. [doi:10.1249/mss.0000000000001715]

37. Prendergast KB, Mackay LM, Schofield GM. The clustering of lifestyle behaviours in New Zealand and their relationship with optimal wellbeing. Int J Behav Med 2016 Oct 4;23(5):571-579. [doi: 10.1007/s12529-016-9552-0] [Medline:26944753]

38. Fernandez ME, Ten Hoor GA, van Lieshout S, Rodriguez SA, Beidas RS, Parcel G, et al. Implementation mapping: using intervention mapping to develop implementation strategies. Front Public Health 2019;7:158. [doi:10.3389/fpubh.2019.00158] [Medline:31275915]

39. Viechtbauer W, Smits L, Kotz D, Budé L, Spigt M, Serroyen J, et al. A simple formula for the calculation of sample size in pilot studies. J Clin Epidemiol 2015 Nov;68(11):1375-1379. [doi: 10.1016/j.jclinepi.2015.04.014] [Medline:26146089]

40. Brooke J. SUS-A quick and dirty usability scale. In: Usability evaluation in industry. London: CRC Press; 1996:189-194.

41. Lund A. Measuring usability with the USE Questionnaire. Usability Interf 2001;8(2):3-6.

42. Brooke J. Usability engineering in office product development. In: Proceedings of the Second Conference of the British Computer Society, human computer interaction specialist group on People and computers: designing for usability. Cambridge: Cambridge University Press; 1986:249-259.

43. Prochaska JO, DiClemente CC. Stages and processes of self-change of smoking: toward an integrative model of change. J Consult Clin Psychol 1983 Jun;51(3):390-395. [doi:10.1037//0022-006x.51.3.390] [Medline:6863699]

44. Bangor A, Staff T, Kortum P, Miller J, Staff T. Determining what individual SUS scores mean: adding an adjective rating scale. J Usability Stud 2009;4(3):114-123.

45. Ortega RM, Pérez-Rodrigo C, López-Sobaler AM. Dietary assessment methods: dietary records. Nutr Hosp 2015 Feb;31(Suppl 3):38-45 [doi:10.3305/nh.2015.31.sup3.8749] [Medline:25719769]

46. Nederlands voedingsstoffenbestand (NEVO). Rijksinstituut voor Volksgezondheid en Milieu. 2019. URL: https://nevo-online.rivm.nl/ [accessed 2019-06-30]

47. Himes JH. New equation to estimate body mass index in amputees. J Am Diet Assoc 1995 Jun;95(6):646. [doi:10.1016/S0002-8223(95)00175-1] [Medline:7759736]

48. Osterkamp LK. Current perspective on assessment of human body proportions of relevance to amputees. J Am Diet Assoc 1995 Feb;95(2):215-218. [doi:10.1016/S0002-8223(95)00050-X] [Medline:7852688]

49. Kyle UG, Genton L, Karsegard L, Slosman DO, Pichard C. Single prediction equation for bioelectrical impedance analysis in adults aged 20--94 years. Nutrition 2001 Mar;17(3):248-253. [doi: 10.1016/s0899-9007(00)00553-0] [Medline:11312069]

50. Washburn RA, Zhu W, McAuley E, Frogley M, Figoni SF. The physical activity scale for individuals with physical disabilities: development and evaluation. Arch Phys Med Rehabil 2002 Feb;83(2):193-200. [doi:10.1053/apmr.2002.27467] [Medline:11833022]

51. Teeuw B, Schwarzer R, Jerusalem M. Dutch Adaptation of the General Self-Efficacy Scale. Berlin; 1994. URL: http://userpage.fu-berlin.de/~health/dutch.htm [accessed 2019-01-07]

52. Barlow JH, Williams B, Wright C. The Generalized Self-Efficacy Scale in people with arthritis. Arthritis Care Res 1996 Jun;9(3):189-196. [doi:10.1002/1529-0131(199606)9:3<189::aid-anr1790090307>3.0.co;2-#] [Medline:8971228]

53. Peter C, Cieza A, Geyh S. Rasch analysis of the General Self-Efficacy Scale in spinal cord injury. J Health Psychol 2014 Apr;19(4):544-555. [doi:10.1177/1359105313475897] [Medline:23463793]

54. Nooijen CFJ, Post MWM, Spijkerman DCM, Bergen MP, Stam HJ, van den Berg-Emons RJG. Exercise self-efficacy in persons with spinal cord injury: psychometric properties of the Dutch translation of the Exercise Self-Efficacy Scale. J Rehabil Med 2013 Apr;45(4):347-350 [doi: 10.2340/16501977-1112] [Medline:23474694]

55. McAuley E. Self-efficacy and the maintenance of exercise participation in older adults. J Behav Med 1993 Feb;16(1):103-113. [doi:10.1007/BF00844757] [Medline:8433355]

56. Vercoulen JH, Swanink CM, Fennis JF, Galama JM, van der Meer JW, Bleijenberg G. Dimensional assessment of chronic fatigue syndrome. J Psychosom Res 1994 Jul;38(5):383-392. [doi: 10.1016/0022-3999(94)90099-x] [Medline:7965927]

57. Makowiec-Dabrowska T, Koszada-Włodarczyk W. The CIS20R Questionnaire and its suitability for prolonged fatigue studies. Med Pr 2006;57(4):335-345. [Medline:17133914]

58. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. Psychiatry Res 1989 May;28(2):193-213. [doi: 10.1016/0165-1781(89)90047-4] [Medline:2748771]

59. Mollayeva T, Thurairajah P, Burton K, Mollayeva S, Shapiro CM, Colantonio A. The Pittsburgh sleep quality index as a screening tool for sleep dysfunction in clinical and non-clinical samples: A systematic review and meta-analysis. Sleep Med Rev 2016 Feb;25:52-73. [doi: 10.1016/j.smrv.2015.01.009] [Medline:26163057]

60. Froehlich-Grobe K, Andresen EM, Caburnay C, White GW. Measuring health-related quality of life for persons with mobility impairments: an enabled version of the short-form 36 (SF-36E). Qual Life Res 2008 Jun;17(5):751-770. [doi:10.1007/s11136-008-9342-5] [Medline:18427950]

61. Aaronson NK, Muller M, Cohen PD, Essink-Bot ML, Fekkes M, Sanderman R, et al. Translation, validation, and norming of the Dutch language version of the SF-36 Health Survey in community and chronic disease populations. J Clin Epidemiol 1998 Nov;51(11):1055-1068. [doi:10.1016/s0895-4356(98)00097-3] [Medline:9817123]

62. Green J, Thorogood N. Qualitative methods for health research. 4th ed. London: SAGE Publications; 2018.

63. Tomczak M, Tomczak E. The need to report effect size estimates revisited. An overview of some recommended measures of effect size. Trends Sport Sci 2014;21(1):19-26. [doi: 10.4135/9781473997448]

64. Fogg B. A behavior model for persuasive design. In: Proceedings of the 4th International Conference on Persuasive Technology. Claremont, CA: ACM Press; 2009:1-7.

65. Vandelanotte C, Spathonis KM, Eakin EG, Owen N. Website-delivered physical activity interventions a review of the literature. Am J Prev Med 2007 Jul;33(1):54-64. [doi:10.1016/j.amepre.2007.02.041] [Medline:17572313]

66. Gilliland J, Sadler R, Clark A, O'Connor C, Milczarek M, Doherty S. Using a smartphone application to promote healthy dietary behaviours and local food consumption. Biomed Res Int 2015;2015:841368. [doi:10.1155/2015/841368] [Medline:26380298]

67. Wang JB, Cadmus-Bertram LA, Natarajan L, White MM, Madanat H, Nichols JF, et al. Wearable sensor/device (Fitbit One) and SMS text-messaging prompts to increase physical activity in overweight and obese adults: a randomized controlled trial. Telemed J E Health 2015 Oct;21(10):782-792 [doi: 10.1089/tmj.2014.0176] [Medline:26431257]

68. Evidence scan: Training professionals in motivational interviewing. The Health Foundation. 2011 Nov. URL: https://www.health.org.uk/sites/default/files/TrainingProfessionalsInMotivationalInterviewing .pdf [accessed 2021-07-05]

69. Hall JA, Horgan G, Murphy NA. Nonverbal communication. Annu Rev Psychol 2019 Jan;70:271-294. [doi:10.1146/annurev-psych-010418-103145] [Medline:30256720]

70. Houlihan BV, Brody M, Everhart-Skeels S, Pernigotti D, Burnett S, Zazula J, et al. Randomized trial of a peer-led, telephone-based empowerment intervention for persons with chronic spinal cord injury improves health self-management. Arch Phys Med Rehabil 2017 Jun;98(6):1067-1076. [doi: 10.1016/j.apmr.2017.02.005] [Medline:28284835]

71. Martin Ginis KA, Ma JK, Latimer-Cheung AE, Rimmer JH. A systematic review of review articles addressing factors related to physical activity participation among children and adults with physical disabilities. Health Psychol Rev 2016 Dec;10(4):478-494. [doi:10.1080/17437199.2016.1198240] [Medline:27265062]

72. van den Berg-Emons RJ, L'Ortye AA, Buffart LM, Nieuwenhuijsen C, Nooijen CF, Bergen MP, et al. Validation of the Physical Activity Scale for individuals with physical disabilities. Arch Phys Med Rehabil 2011 Jun;92(6):923-928. [doi:10.1016/j.apmr.2010.12.006] [Medline:21507382]

Abbreviations

BIA:	Bioelectrical impedance analysis
CIS20R:	Checklist individual strength
LLA:	Lower limb amputation
MET:	Metabolic equivalents of task
mHealth:	Mobile health
PASIPD:	Physical Activity Scale for Individuals with Physical Disabilities
PSQI:	Pittsburgh Sleep Quality Index
SCI:	Spinal cord injury
SF-36E:	Short-Form Health Survey Enabled
SUS:	System usability scale
USE:	Usefulness, Satisfaction and Ease of use
WC:	Waist circumference
WHEELS:	Wheelchair ExercisE and Lifestyle Study

Supplementary appendix 1. Development process of the WHEELS app

Step 1: needs assessment and intervention goals

At the start of the project a planning group was established to help develop the intervention. This planning group consisted of a representative of the target group (i.e., board member of the Dutch SCI patient association), rehabilitation professionals (i.e., exercise therapists and occupational therapists) working at two Dutch rehabilitation centers (Reade, Amsterdam and Heliomare, Wijk aan Zee), human movement scientists, health scientists, eHealth experts and a software development manager. Subsequently, the lifestyle behaviors – in terms of physical activity, nutrition and relaxation/sleep – and related problems in health and health-related quality of life among persons with SCI or LLA, were investigated through a literature search and focus group interviews. In addition, determinants of these lifestyle behaviors and contributing environmental conditions were identified. To analyze all data the PRECEDE model was used [1].

It has been shown that the PA level (measured by accelerometry) of wheelchair users with SCI and wheelchair users with LLA caused by vascular diseases, is less than 40% of the able-bodied level [2,3]. In 2017, only 12% of Dutch people with a motor impairment aged 12 years and older, including persons with SCI or LLA, met the Dutch physical activity guidelines and 21% practiced sports weekly versus, respectively, 46% and 54% of the same age group in the general population [4,5]. Prolonged sedentary behavior is common in wheelchair users and considered as a modifiable risk factor for cardiovascular diseases [6]. New SCI PA guidelines were published in 2017 including an infographic, focused on wheelchair users [7,8]. Because amputation PA guidelines are not specified for wheelchair users, the SCI PA guidelines were also applied for the LLA individuals as intervention goal, as this guideline is more applicable to persons for whom prolonged sitting is unavoidable. In addition, it has been shown that persons with SCI and LLA have a poorer diet quality compared to the general population, characterized by inadequate intake of dairy, fruit, whole grain foods and fibre, and a too high intake of fat, sugar and sodium [9–11]. Furthermore, sleep disturbances and psychological distress have been reported in both groups, and fatigue is known to negatively affect the lives of persons with SCI [12–18].These unhealthy lifestyle behaviors and lack of vitality are directly, or via being overweight, linked to an increased risk of physical and psychological comorbidity [11,19,20] and a reduced quality of life [21,22].

These findings from the literature were confirmed by a total of seven focus groups. Five focus groups with wheelchair users (n=25) with an average age of 58 years ranging between 39 and 75 years took place. Most included participants were fully adapted to their chronic condition with an average time of 9 years with a range between 0 and 55 years since the onset of their chronic condition. Two focus groups with rehabilitation professionals (n=11), with an average of 10 years of working experience ranging between one and 30 years, were held to gain a clearer picture of the needs of wheelchair users regarding lifestyle guidance [23]. Based on this needs assessment the following intervention goals were determined.

1. Wheelchair users with SCI or LLA comply with the scientific exercise guidelines for adults with SCI [7].
2. Wheelchair users with SCI or LLA have a healthy energy balance;
3. Wheelchair users with SCI or LLA have a healthy balance between exercise and sleep/relaxation; and
4. After the rehabilitation phase, rehabilitation professionals offer lifestyle guidance to wheelchair users with SCI or LLA with support of the application.

Step 2: matrices of change objectives

In this step, the desired health promoting behaviors were specified. First, the desired behaviors of wheelchair users (intervention goals 1–3) and rehabilitation professionals (intervention goal 4), were broken down into subcomponents or performance objectives by answering the question: "What does the wheelchair user or professional need to do to attain the desired behavior?". Subsequently, a stakeholder group (n=19) – consisting of wheelchair users with either SCI or LLA, partners of wheelchair users, rehabilitation professionals, health scientists and human movement scientists – was asked to rate the importance of achieving these performance objectives for developing the desired health promoting behaviors on a seven-point rating scale ranging from "not important" to "very important". Based on this stakeholder analysis twelve performance objectives for physical activity and exercise behavior, seven for dietary behavior, five for sleep and relaxation behavior and four for the behavior of rehabilitation professionals were selected to further use in developing the intervention.

Secondly, modifiable behavioral determinants that should be targeted with the intervention were selected based on the results from the aforementioned focus group study [23,24], a literature search, a stakeholder analysis and theory. In the stakeholder analysis, 23 stakeholders – largely the same persons who ranked the performance objectives – rated the importance of a large number of determinants for developing and/or maintaining healthy physical activity, dietary and relaxation behavior on a seven-point rating scale ranging from "not important" to "very important". In the end, six modifiable determinants were selected to target in wheelchair users, i.e., attitude [25], awareness, self-efficacy [26], knowledge [27], outcome expectations [28,29] and skills [30]. To target in rehabilitation professionals, the determinants perceived barriers, knowledge, social support and skills were selected.

Finally, matrices of change objectives were created by combining the performance objectives with the determinants. Change objectives answer the question what needs to change in the determinant for the wheelchair user or rehabilitation professional to achieve the performance objective. These matrices are provided in the Matrices of change objectives created in the WHEELS project to direct the development of a mobile lifestyle intervention for wheelchair users).

Step 3: behavior change methods and practical applications

After creating the matrices of change objectives, theory- and evidence-based methods for achieving the intervention goals were chosen based on the determinants selected in step 2. These methods were then translated into applications features, i.e. specific strategies to deliver the method in a way that suits both the wheelchair users and rehabilitations professionals and the intended eHealth setting [31]. The behavior change methods and matching practical strategies were derived from various books and scientific articles, the focus group results and a stakeholder survey [32–40]. In this stakeholder survey an initial list of practical strategies was presented to 19 stakeholders with the question to rate the importance of each strategy for developing and/or maintaining healthy physical activity, dietary and relaxation behavior on a seven-point rating scale ranging from “not important” to “very important”. The selection process yielded 16 methods – i.e., tailoring, self-monitoring, providing feedback, modeling, facilitation, direct experience, persuasive communication, active learning, consciousness raising, personalizing risks and benefits, goal setting, setting graded tasks, planning coping responses, motivational interviewing, guided practice and participation – which were mainly derived from the social cognitive theory, the elaboration likelihood model and transtheoretical model of change [32]. An overview of the determinants, their linked behavior change methods and practical strategies is provided in the matrices of change objectives presented after step 6.

Step 4: pretesting, program refinement and production

In step 4, the information collected in IM-steps 1 to 3 was used to develop intervention materials and the mobile lifestyle app. First, six personas were created to ensure the lifestyle app would match the needs and potential of a heterogeneous group of future users. In order to create heterogeneous personas, variation was applied on the following aspects in order to ensure heterogeneity in the different personas: age, sex, educational level, severity chronic condition, physical function, mental state and social situation. A wide range in age was applied 26 – 75 with a 4/2 male/female ratio as it would represent Dutch society most regarding the presence of

SCI and LLA. Severity and therefore physical function ranged in case of SCI between paraplegia and tetraplegia with complete or incomplete lesion. In case of LLA, severity ranged between unilateral transtibial amputation and bilateral amputation. Three personas were created with an SCI and three with LLA. Personas were constructed in such a way that the combination of characteristics of these aspects would be very feasible and would represent a potential future user of the app. Unlikely combination were avoided, such as: elderly with young children. Three rehabilitation professionals reviewed the personas and made suggestions for improvement to ensure they were a true reflection of the wheelchair users they encounter in their daily practice. Second, two independent eHealth experts linked the list of practical strategies to design principles for persuasive system content and functionality based on the Persuasive Systems Design model [41]. They translated the list of practical strategies and linked design principles into user requirements and checked whether these met the needs of the personas. Finally, based on the list of practical strategies and user requirements, the app was built by the Dutch software provider Virtuagym using their already existing software solutions for the fitness and health industry.

Figure 1 shows the structure of the WHEELS-app. The tiles on the home screen direct the user to the different parts. The "Community" includes a start instruction and four groups that provide information on: 1) physical activity and exercise; 2) healthy eating and energy expenditure; 3) sleep and relaxation; and 4) lifestyle change tools, such as creating an action plan, coping plan and payoff matrix. A fifth group allows users to ask questions, share experiences and tips, and interact with each other. The "Individual exercises" and "Exercise program" tiles direct to an exercise database with more than 250 custom-built exercises suitable for wheelchair users and pre-programmed exercise routines. In the "Food" part users can keep a food diary and get insight into their daily energy and nutrient intake. In the "Sleep & Relaxation" environment relaxation exercises are offered, in addition to knowledge transfer about balancing physical and mental load and capacity, healthy sleeping and relaxation habits. Behind the "Progress" tile users can get insight into changes in predefined health and fitness parameters, such as weight and body mass index (BMI). In addition, the app offers the ability to take on various lifestyle challenges. For example, the user can participate in the 90-minute weekly handcycling challenge and compare his/her performance with that of other participants. Finally, the app contains a calendar in which exercises and exercise routines can be scheduled.

The information and relaxation exercises provided in the community have been developed by the project group in collaboration with fourth-year bachelor students Sport studies, Functional Exercise Therapy and Nutrition and Dietetics who conducted literature research and interviewed rehabilitation professionals with expertise in exercise, nutrition and relaxation/sleep. The information on exercise and physical activity is based on the scientific exercise guidelines for adults with SCI [7], exercise guidelines of the American College of Sports Medicine [42] and the Dutch physical activity guidelines [43]. The information on healthy nutrition and energy expenditure is based on the guidelines and advices of the Dutch Nutrition Centre [44] and the brochure 'Food, weight and health for people with SCI' of the Swedish Spinalis Foundation [45], which was translated into Dutch in collaboration with the author (A-C Lagerström) and dieticians in the Dutch rehabilitation centers.

The WHEELS-app can be used stand-alone or guided. Individuals are in the position to plan existing exercise programs in their calendar, create own exercise programs and create their nutrition plans. Information and a format is shared with users on how to create an action plan. With guided use, the rehabilitation or lifestyle professional is assigned rights with which personal exercise programs and nutrition plans can be created and assigned to individuals by the rehabilitation or lifestyle professional to ensure correct choices of exercises and reasonable nutrition plans. The professional has access to the user profiles with progress tracking information and can involve individuals in lifestyle challenges for additional motivation. Communication with wheelchair users takes place via messages on their profile pages or e-mail. In addition, coaching can be done by phone.

After development, the individual parts of the app were pre-tested on ease of use and satisfaction in a user study among 24 wheelchair users and 5 rehabilitation professionals. Based on the results, minor adjustments were made with regard to the instruction and findability of the various parts of the app. Subsequently, the complete app was tested in a pilot study.

Step 5: program implementation plan

For the purpose of the pilot study, the WHEELS-app was implemented on a small scale via the two participating rehabilitation centers. Part of the implementation strategy was to involve wheelchair users and rehabilitation professionals in the development of the mobile lifestyle application. After processing the results of the pilot study, a strategy was developed for the national implementation of the WHEELS-app. Theory and empiric literature on the implementation of health promotion programs were consulted [32,46,47]. In addition, interviews were held with intermediate organizations with a close connection with wheelchair users and rehabilitation professionals to gain insight into the barriers and stimulating factors for successful adoption, implementation and maintenance of the WHEELS-app. The Measurement Instrument for Determinants of Innovations (MIDI) was used to prepare these interviews [46]. Based on the results, a plan was developed to ensure that the WHEELS-app would be adopted, implemented and maintained.

Step 6: program evaluation plan

An evaluation plan was developed for the pilot study. This plan describes both the process and the effect evaluation. The process evaluation aimed to determine the usability and feasibility of the mobile lifestyle intervention. The effect evaluation aimed to assess whether the intervention has the desired effects on the lifestyle, health and quality of life of wheelchair users with SCI or LLA. After the intervention has been improved based on the results of the pilot study, a more extensive evaluation plan will be developed that can be used to evaluate the intervention after national implementation.

Matrices of change objectives created in the WHEELS project to direct the development of a mobile lifestyle intervention for wheelchair users

Matrix of change objectives (performance objectives linked to behavioral determinants) showing the steps that wheelchair users (WU) with a spinal cord injury or lower limb amputation should take to meet the physical activity and exercise guidelines.

Performance objectives	**Determinants**				
	Attitude	***Awareness***	***Self-efficacy and skills***	***Knowledge***	***Outcome expectations***
Precontemplation and contemplation stage					
PO1. WU are acquainted with the applicable physical activity and exercise guidelines.	At1a. WU are positive about reading the applicable physical activity and exercise guidelines.	Aw1a. WU are aware of the existence of applicable physical activity and exercise guidelines.	SeS1a. WU are confident that they can find and understand the applicable physical activity and exercise guidelines. SeS1b. WU show where they can find the applicable physical activity and exercise guidelines.	Kn1a. WU describe when they meet the applicable physical activity and exercise guidelines.	Oe1a. WU expect that knowledge of the applicable physical activity and exercise guidelines will help them to become physically active or start exercising.
Preparation and action stage					
PO2. WU give reasons for being physically active and exercise participation.		Aw2a. WU are aware of the importance of physical activity and exercise.		Kn2a. WU list the advantages of physical activity and exercise participation.	Oe2a. WU have realistic expectations regarding the benefits of physical activity and exercise participation.

PO3. WU decide to become (more) physically active and start exercising (more often).	At3a. WU have a positive attitude towards participation in physical activity and exercise activities.		SeS3a. WU have confidence that they will be able to be physically active and/ or exercise (more often).		Oe3a. WU expect that participation in physical activity and exercise activities will have a positive effect on their health and well-being.
PO4. WU set goals and make their own physical activity and exercise plan.	At4a. WU have a positive attitude towards making an action plan.	Aw4a. WU are aware that setting goals and making an action plan helps them to become and stay physically active.	SeS4a. WU are confident that they can set realistic physical activity and exercise goals. SeS4b. WU show their action plan.	Kn4a. WU name physical activity and exercise activities that match their goals and possibilities. Kn4b. WU formulate SMART physical activity and exercise goals. Kn4c. WU describe what an action plan must meet.	Oe4a. WU expect that setting goals and drawing up an action plan will help them to become and stay physically active and fit.
PO5. WU (who need it) ask help from their social environment to become and stay physically active.	At5a. WU have a positive attitude towards asking their social environment for help in becoming and staying physically active.	Aw5a. WU are aware of the will and possibilities of their social environment to help them become and stay physically active.	SeS5a. WU are confident that they can ask their social environment for help to become and stay physically active.		Oe5a. WU have realistic expectations of the help and support that their social environment can provide in becoming and staying physically active.

PO6. WU are acquainted with the physical activity and exercise possibilities in their living environment.	At6a. WU have a positive attitude towards exercise and physical activity close to home.	Aw6a. WU are aware that travel time and transport problems are barriers to becoming and staying physically active.	SeS6a. WU are confident that they can identify the exercise and physical activity options in their living environment. SeS6b. WU show the sports and exercise options in their living environment.	Kn6a. WU show where they can find information about suitable exercise and physical activity options in their living environment. Kn6b. WU name suitable sports activities that are offered in and around their place of residence.	Oe6a. WU expect that awareness of physical activity and exercise opportunities close to home will facilitate a physically active lifestyle.
PO7. WU are more physically active in everyday life.	At7a. WU have a positive attitude towards being more physically active in daily life.	Aw7a. WU are aware of their current level of physical activity. Aw7b. WU are aware of moments in daily life when they can be more physically active.	SeS7a. WU are confident that they can overcome barriers and manage to be more physically active in everyday life.	Kn7a. WU name moments in everyday life when they can be more physically active. Kn7b. WU describe how they can increase their level of physical activity in daily life.	Oe7a. WU expect that the incorporation of physical activity into daily life has a positive effect on their health and wellbeing.
PO8. WU train their cardiovascular fitness.	At8a. WU have a positive attitude towards improving their cardiovascular fitness.	Aw8a. WU are aware of the importance of good cardiovascular fitness.	SeS8a. WU are confident that they can train their cardiovascular fitness.	Kn8a. WU describe exercises and activities with which they can train their cardiovascular fitness.	Oe8a. WU expect that they can improve or maintain their cardiovascular fitness through exercise.
PO9. WU do muscle strengthening activities.	At9a. WU have a positive attitude towards muscle strengthening activities.	Aw9a. WU are aware of the importance of muscle strengthening activities.	SeS9a. WU are confident that they can train their muscle strength.	Kn9a. WU describe the ways in which they can train their muscle strength.	Oe9a. WU expect their muscle strength to improve or be maintained through exercise.

Maintenance stage					
PO10. WU have solutions for dealing with difficulties regarding exercise and physical activity.	At10a. WU have a positive attitude towards making a coping plan.	Aw10a. WU are aware of possible pitfalls in exercise and physical activity planning.	SeS10a. WU are confident that they will be able to keep exercising and stay physically active in difficult situations. SeS10b. WU show their coping plan.	Kn10a. WU describe strategies to keep exercising regularly in difficult situations. Kn10b. WU describe how to make a coping plan.	Oe10a. WU expect that making a coping plan will help them to become and stay physically active.
PO11. WU enjoy their exercise and physical activity routine.		Aw11a. WU are aware that fun helps to maintain an exercise and physical activity routine.	SeS11a. WU are confident that they can enjoy exercise and physical activity.	Kn11a. WU describe sports and exercise activities that they enjoy.	Oe11a. WU expect that they will better adhere to sports and exercise activities that they enjoy.
PO12. WU have made it a routine to be physically active in daily life.	At12a. WU have a positive attitude towards making an exercise routine.	Aw12a. WU are aware of the importance of regular physical activity and exercise.	SeS12a. WU are confident that they can make a routine of their exercise and physical activity behavior.		Oe12a. WU expect that regular exercise and physical activity will have a positive effect on their health.

Matrix of change objectives (performance objectives linked to behavioral determinants) showing the steps that wheelchair users (WU) with a spinal cord injury or lower limb amputation should take to obtain a healthy energy balance.

Performance objectives	**Determinants**				
	Attitude	***Awareness***	***Self-efficacy and skills***	***Knowledge***	***Outcome expectations***
Preparation and action stage					
PO1. WU decide to work on a healthier diet.	At1a. WU have a positive attitude towards a healthy diet.		EV1a. WU are confident that they can eat healthier.		Oe1a. WU expect that adopting a healthy diet will have a positive effect on their health and wellbeing.
PO2. WU choose healthy food products.	At2a. WU have a positive attitude towards healthy food products.		SeS2a. WU are confident that they can choose healthy food products in the store.	Kn2a. WU know what healthy food products are.	Oe2a. WU expect healthy food products to positively influence their health and wellbeing.
PO3. WU adjust their energy intake to their energy expenditure.	At3a. WU have a positive attitude towards monitoring their weight.	Aw3a. WU are aware of their changed energy expenditure as a result of their illness and wheelchair use.	SeS3a. WU are confident that they can find out their daily calorie needs. SeS3b. WU are confident that they can adjust their energy intake to their energy expenditure. SeS3c. WU show how they match their energy intake to their energy expenditure.	Kn3a. WU describe how they can find out and calculate the energy value of foods. Kn3b. WU describe how they match their energy intake to their energy consumption.	Oe3a. WU expect that matching their energy intake to their energy expenditure will have a positive effect on their health and wellbeing.

			SeS3d. WU will consult a dietician if they need help adjusting their energy intake to their energy consumption.		
PO4. WU have a varied diet.	At4a. WU have a positive attitude towards a varied diet.	Aw4a. WU describe how varied their current diet is.	SeS4a. WU are confident that they can adopt a varied diet. SeS4b. WU show that they can eat varied meals.	Kn4a. WU describe a healthy and varied diet.	Oe4a. WU expect a varied diet to positively affect their health and wellbeing.
PO5. WU have realistic expectations of the consequences of a healthier diet.		Aw5a. WU are aware that a healthier diet leads to weight loss or a healthier body composition only if their energy expenditure is higher than their energy intake.		Kn5a. WU describe the potential health consequences of a healthy and unhealthy diet. Kn5b. WU list the conditions for healthy weight loss.	
PO6. WU involve their social environment in adjusting their diet.		Aw6a. WU are aware of the influence of their social environment on their diet.	SeS6a. WU are confident that their social environment will support them in adjusting their diet.	Kn6a. WU describe how their social environment can support them in adjusting their diet.	

Maintenance stage					
PO7. WU have made a habit of eating healthy.		Aw7a. WU are aware of situations in which it is difficult to continue eating healthy.	SeS7a. WU are confident that they can maintain a healthy diet. SeS7b. WU show a coping plan.		

Matrix of change objectives (performance objectives linked to behavioral determinants) showing the steps that wheelchair users (WU) with a spinal cord injury or lower limb amputation should take to obtain a healthy balance between exercise and relaxation

Performance objectives	**Determinants**				
	Attitude	***Awareness***	***Self-efficacy and skills***	***Knowledge***	***Outcome expectations***
Preparation and action stage					
PO1. WU have good body awareness.	At1a. WU recognize the importance of body awareness. At1b. WU are open to learning more about body awareness and coping with fatigue.	Aw1a. WU are aware of their body signals. Aw1b. WU are aware of their body posture. Aw1c. WU describe how they recognize fatigue.	SeS1a. WU are confident that they can develop good body awareness.	Kn1a. WU know what body awareness is and how they can develop it.	Oe1a. WU expect good body awareness to positively affect their health and wellbeing.
PO2. WU apply principles related to balancing physical demand/load and capacity.	At2a. WU have a positive attitude towards applying principles related to balancing physical demand/load and capacity.	Aw2a. WU are aware of what is demanded from their body and the capacity of their body.	SeS2a. WU are confident that they can apply principles related to balancing physical demand and capacity.	Kn2a. WU name principles related to balancing physical load and capacity.	Oe2a. WU expect that applying principles related to balancing physical load and capacity can protect them from going beyond their physical limits.

			SeS2b. WU show that they can apply principles related to balancing physical demand and capacity. SeS2c. WU show how they can determine their degree of fatigue.		
PO3. WU have solutions for coping with stressful situations.	At3a. WU recognize that they experience (sometimes) stressful situations. At3b. WU are willing to pay attention to coping with stressful situations.	Aw3a. WU are aware of situations that they experience as stressful.	SeS3a. WU are confident that they can influence stressful situations.	Kn3a. WU describe how they can make situations they experience as stressful less stressful.	Oe3a. WU expect that recognizing stressful situations and thinking about solutions will lead to less stress.
PO4. WU can relax.	At4a. WU are positive about relaxation exercises.	Aw4a. WU are aware of the amount of tension in their body. Aw4b. WU are aware of the importance of rest and relaxation for the recovery of their body.	SeS4a. WU trust they can rest and relax. SeS4b. WU show relaxation exercises.		Oe4a. WU expect that relaxation exercises have a positive effect on their health and wellbeing.

PO5. WU have healthy sleeping habits.	At5a. WU have a positive attitude towards developing and maintaining healthy sleeping habits.	Aw5a. WU are aware of the influence of sleep on exercise and dietary behavior.	SeS5a. WU are confident that they can develop healthy sleeping habits. SeS5b. WU show that they can apply healthy sleeping habits.	Kn5a. WU describe habits that promote sleep.	Oe5a. WU expect healthy sleeping habits to positively influence their health and wellbeing.

Matrix of change objectives (performance objectives linked to behavioral determinants) showing the steps that rehabilitation or lifestyle professionals should take to continue providing lifestyle guidance to wheelchair users with spinal cord injury or lower limb amputation after the rehabilitation phase.

Performance objectives	**Determinants**			
	Perceived barriers	***Knowledge***	***Social support***	***Skills***
PO1. Professionals provide lifestyle counselling aimed at promoting physical activity/ exercise, healthy diet and rest/ relaxation after the rehabilitation phase.	PB1a. Professionals anticipate barriers to the provision of lifestyle counselling to WU after the rehabilitation phase.		SS1a. Professionals motivate WU to be physically active, exercise, eat healthy and pay attention to rest/ relaxation and healthy sleep habits.	S1a. Professionals show how they help WU to formulate and pursue personal lifestyle goals.
PO2. Professionals encourage WU to comply with the applicable physical activity and exercise guidelines.	PB2a. Professionals anticipate factors that prevent them from encouraging WU to comply with the applicable physical activity and exercise guidelines.	Kn2a. Professionals describe how WU can comply with the applicable physical activity and exercise guidelines.	SS2a. Professionals motivate WU to comply with the applicable physical activity and exercise guidelines.	S2a. Professionals show how they encourage WU to comply with the applicable physical activity and exercise guidelines.
PO3. Professionals encourage WU to develop and maintain a healthy energy balance.	PB3a. Professionals anticipate barriers that prevent them from encouraging WU to develop and maintain a healthy energy balance.	Kn3a. Professionals describe how WU can develop and maintain a healthy energy balance.	SS3a. Professionals motivate WU to develop and maintain a healthy energy balance.	S3a. Professionals show how they encourage WU to develop and maintain a healthy energy balance.
PO4. Professionals encourage WU to develop a healthy balance between exercise and rest/relaxation.	PB4a. Professionals anticipate barriers that prevent them from encouraging WU to develop a healthy balance between exercise and rest/ relaxation.	Kn4a. Professionals describe how WU can develop a healthy balance between exercise and rest/ relaxation.	SS4a. Professionals motivate WU to develop a healthy balance between exercise and rest/ relaxation.	S4a. Professionals show how they stimulate WU to develop a healthy balance between exercise and rest/ relaxation.

Behavior change methods and practical strategies used to achieve the intervention goals of the WHEELS project.

Table 1. Behavior change methods and practical strategies that have been selected to change the **attitude** and **outcome expectations** of wheelchair users in order to achieve the change objectives, and with this the intervention goals.

Change objectives aimed at meeting the applicable physical activity and exercise guidelines	Behavior change method	Practical strategy
At1a. WU are positive about reading the applicable physical activity and exercise guidelines. Oe1a. WU expect that knowledge of the applicable physical activity and exercise guidelines will help them to become physically active or start exercising.	Persuasive communication (Elaboration Likelihood Model)[32,48] Tailoring (Trans-Theoretical Model)[32,34]	Written messages and an infographic providing information and arguments to become familiar with the physical activity and exercise guidelines for persons with a SCI or LLA.
Oe2a. WU have realistic expectations regarding the benefits of physical activity and exercise participation.	Self-monitoring and Feedback (Social Cognitive Theory) [32,37]	Monitoring and graphical presentation of progress on self-formulated physical activity and exercise goals.
At3a. WU have a positive attitude towards participation in physical activity and exercise activities. Oe3a. WU expect that participation in physical activity and exercise activities will have a positive effect on their health and wellbeing.	Persuasive communication (Elaboration Likelihood Model) [32,48] Modeling (Social Cognitive Theory) [32,37]	Written messages providing information about the pros of a physically active lifestyle and exercise and cons of sedentary behavior. Videos and/or quotes from role models demonstrating what physical activity and exercise have brought them. Ability to exchange experiences about overcoming barriers and the benefits of physical activity and exercise in an online community.
At4a. WU have a positive attitude towards making an action plan. Oe4a. WU expect that setting goals and drawing up an action plan will help them to become and stay physically active and fit.	Tailoring (Trans-Theoretical Model) [32,37] Facilitation (Social Cognitive Theory) [32,37]	Providing a tailored example of an action plan, and a format to facilitate creating your own action plan.

Table 1. Continued from previous page.

At5a. WU have a positive attitude towards asking their social environment for help in becoming and staying physically active. Oe5a. WU have realistic expectations of the help and support that their social environment can provide in becoming and staying physically active.	Direct experience (Learning Theories)[32] Modeling (Social Cognitive Theory)[32,37]	Possibility to ask questions to fellow wheelchair users. Ability to contact a lifestyle coach (when using the app blended). Role models share how they got help and what it brought them.
At6a. WU have a positive attitude towards exercise and physical activity close to home. Oe6a. WU expect that awareness of physical activity and exercise opportunities close to home will facilitate a physically active lifestyle.	Persuasive communication (Elaboration Likelihood Model)[32,48] Facilitation (Social Cognitive Theory)[32,37]	Written messages providing information and arguments to look for suitable exercise and physical activities in the residential environment. Exercise database and tailored fitness work-outs that can be performed in the home environment. Link to national disability sports finder website which enables searching for a sports club by area.
Change objectives aimed at meeting the applicable physical activity and exercise guidelines	**Behavior change method**	**Practical strategy**
At7a. WU have a positive attitude towards being more physically active in daily life. Oe7a. WU expect that the incorporation of physical activity into daily life has a positive effect on their health and wellbeing.	Modeling (Social Cognitive Theory)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Videos and/or quotes from role models showing that being more physically active in daily life has brought them health benefits. Written messages providing information and arguments to incorporate physical activity into daily life.
At8a. WU have a positive attitude towards improving their cardiovascular fitness. Oe8a. WU expect that they can improve or maintain their cardiovascular fitness through exercise.	Persuasive communication (Elaboration Likelihood Model)[32,48] Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Written messages providing information and arguments to train cardiovascular fitness. Exercise database and tailored fitness work-outs including cardiovascular exercises for wheelchair users.

Table 1. Continued from previous page.

At9a. WU have a positive attitude towards muscle strengthening activities. Oe9a. WU expect their muscle strength to improve or be maintained through exercise.	Persuasive communication (Elaboration Likelihood Model)[32,48] Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Written messages providing information and arguments to train muscle strength. Exercise database and tailored fitness work-outs including cardiovascular exercises for wheelchair users.
At10a. WU have a positive attitude towards making a coping plan. Oe10a. WU expect that making a coping plan will help them to become and stay physically active.	Tailoring (Trans-Theoretical Model)[32,34] Facilitation (Social Cognitive Theory)[32,37]	Providing a tailored example of a coping plan, and a format to facilitate creating your own coping plan.
Oe11a. WU expect that they will better adhere to sports and exercise activities that they enjoy.	Modeling (Social Cognitive Theory)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Videos and/or quotes from role models showing that it is easier to maintain a sports or exercise activity if you enjoy it. Written messages providing arguments to be physically active in a way that suits you and that you enjoy.
At12a. WU have a positive attitude towards making an exercise routine. Oe12a. WU expect that regular exercise and physical activity will have a positive effect on their health.	Modeling (Social Cognitive Theory)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Videos and/or quotes from role models showing that regular physical activity has improved their fitness, health and wellbeing. Providing information and arguments that support the importance of regular physical activity and exercise.
Change objectives aimed at developing and maintaining a healthy energy balance	**Behavior change method**	**Practical strategy**
At1a. WU have a positive attitude towards a healthy diet. Oe1a. WU expect that adopting a healthy diet will have a positive effect on their health and wellbeing.	Persuasive communication (Elaboration Likelihood Model)[32,48] Modeling (Social Cognitive Theory)[32,37]	Written messages providing information and arguments for the importance of a healthy diet for wheelchair users. Videos and/or quotes from role models who share positive experiences with adjusting their diet.
At2a. WU have a positive attitude towards healthy food products. Oe2a. WU expect healthy food products to positively influence their health and wellbeing.	Direct experience (Learning Theories)[32] Self-monitoring and Feedback (Social Cognitive Theory)[32,37]	Providing personalized feedback on daily calorie and nutrient intake.

Table 1. Continued from previous page.

Change objectives aimed at developing and maintaining a healthy energy balance	Behavior change method	Practical strategy
At3a. WU have a positive attitude towards monitoring their weight. Oe3a. WU expect that matching their energy intake to their energy expenditure will have a positive effect on their health and wellbeing.	Facilitation (Social Cognitive Theory)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Monitoring and graphical presentation of the course of body weight. Written messages providing information and arguments for pursuing a healthy body-mass index.
At4a. WU have a positive attitude towards a varied diet. Oe4a. WU expect a varied diet to positively affect their health and wellbeing.	Persuasive communication (Elaboration Likelihood Model)[32,48] Facilitation (Social Cognitive Theory)[32,37]	Written messages providing information and arguments for adopting a varied diet. Possibility to exchange healthy recipes.
Change objectives aimed at developing and maintaining a healthy balance between exercise and rest/relaxation.	**Behavior change method**	**Practical strategy**
At1a. WU recognize the importance of body awareness. At1b. WU are open to learning more about body awareness and coping with fatigue. Oe1a. WU expect good body awareness to positively affect their health and wellbeing.	Persuasive communication (Elaboration Likelihood Model)[32,48] Facilitation (Social Cognitive Theory)[32,37]	Written messages providing information and arguments for developing good body awareness. Tips and tricks for developing body awareness and dealing with fatigue.
At2a. WU have a positive attitude towards applying principles related to balancing physical demand/load and capacity. Oe2a. WU expect that applying principles related to balancing physical load and capacity can protect them from going beyond their physical limits.	Facilitation (Social Cognitive Theory)[32,37] Modeling (Social Cognitive Theory)[32,37]	Providing an explanation of the load and capacity model and practical tips to balance physical demand and capacity. Videos and/or quotes from role models showing what balancing demand and capacity has brought them.
At3a. WU recognize that they experience (sometimes) stressful situations. At3b. WU are willing to pay attention to coping with stressful situations. Oe3a. WU expect that recognizing stressful situations and thinking about solutions will lead to less stress.	Active learning (Elaboration Likelihood Model)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Exercise to identify factors that consume and provide physical and mental energy. Written messages providing information and arguments for preventing stress to promote health.

Table 1. Continued from previous page.

At4a. WU are positive about relaxation exercises. Oe4a. WU expect that relaxation exercises have a positive effect on their health and wellbeing.	Persuasive communication (Elaboration Likelihood Model)[32,48] Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Written messages providing information and arguments to encourage doing relaxation exercises. Providing relaxation exercises tailored for wheelchair users with SCI and LLA.
At5a. WU have a positive attitude towards developing and maintaining healthy sleeping habits. Oe5a. WU expect healthy sleeping habits to positively influence their health and wellbeing.	Persuasive communication (Elaboration Likelihood Model)[32,48]	Written messages and a brochure providing information, tips and arguments to adopt healthy sleeping habits.

Table 2. Behavior change methods and practical strategies that have been selected to change the **awareness** of wheelchair users in order to achieve the change objectives, and with this the intervention goals.

Change objectives aimed at meeting the applicable physical activity and exercise guidelines	Behavior change method	Practical strategy
Aw1a. WU are aware of the existence of applicable physical activity and exercise guidelines.	Facilitation (Social Cognitive Theory)[32,37]	Sharing a pdf and infographic of the physical activity and exercise guidelines for people with a SCI and people with a LLA. Additionally, the guidelines are summarized in short messages that are shared in an online community group around exercise and physical activity.
Aw2a. WU are aware of the importance of physical activity and exercise.	Personalize risk and benefits (Health Belief Model)[32,35] Persuasive communication (Elaboration Likelihood Model)[32,48]	Written messages providing information about personal costs or risks of sedentary behavior and arguments to exercise, become and stay physically active.
Aw4a. WU are aware that setting goals and making an action plan helps them to become and stay physically active.	Persuasive communication (Elaboration Likelihood Model)[32,48]	Providing written information and arguments to set goals and create an action plan.
Aw5a. WU are aware of the will and possibilities of their social environment to help them become and stay physically active.	Consciousness raising (Trans-Theoretical Model)[32,34] Persuasive communication (Elaboration Likelihood Model)[32,48]	Written messages providing information about risks of not involving the social environment, and arguments to ensure social support in lifestyle change and the maintenance of healthy behavior. Short written messages in the online community. In the face-to-face consultation at the start of the intervention attention is paid to the role that the social environment plays in behavioral change (only applies to blended use of the lifestyle app).

Table 2. Continued from previous page.

Aw6a. WU are aware that travel time and transport problems are barriers to becoming and staying physically active.	Consciousness raising (Trans-Theoretical Model)[32,34]	Written messages containing information about the exercise barriers travel time and transport. Underlining the importance of looking for an exercise of physical activity in the residential area and the opportunity to exercise at home.
Aw7a. WU are aware of their current level of physical activity. Aw7b. WU are aware of moments in daily life when they can be more physically active.	Self-monitoring and Feedback (Social Cognitive Theory)[32,37] Consciousness raising (Trans-Theoretical Model)[32,34]	Exercise and physical activity diary that provides insight into the daily exercise and physical activity pattern. Possibility to link a wrist-worn activity monitor to the app. Written messages providing information and examples of increasing physical activity during daily activities (tiny habits).
Aw8a. WU are aware of the importance of good cardiovascular fitness. Aw9a. WU are aware of the importance of muscle strengthening activities.	Consciousness raising (Trans-Theoretical Model)[32,34]	The exercise and physical activity guidelines for people with SCI and people with LLA are available through the lifestyle app. Additionally, the importance of cardiovascular fitness and muscle strengthening activities is explained in short written messages.
Change objectives aimed at meeting the applicable physical activity and exercise guidelines	**Behavior change method**	**Practical strategy**
Aw10a. WU are aware of possible pitfalls in exercise and physical activity planning.	Consciousness raising (Trans-Theoretical Model)[32,34] Persuasive communication (Elaboration Likelihood Model)[32,37]	Written information and arguments to encourage identifying and anticipating factors that hinder physical activity and exercise.
Aw11a. WU are aware that fun helps to maintain an exercise and physical activity routine.	Consciousness raising (Trans-Theoretical Model)[32,34]	Written messages providing information about the consequences of participating in unsuitable, unenjoyable exercise activities, and arguments to be physically active in a way that suits you and that you do enjoy.

Table 2. Continued from previous page.

Aw12a. WU are aware of the importance of regular physical activity and exercise.	Consciousness raising (Trans-Theoretical Model)[32,34] Persuasive communication (Elaboration Likelihood Model)[32,48]	Written messages providing information and arguments to exercise and to be physically active on a regular basis. Advise to plan activities using an action plan.
Change objectives aimed at developing and maintaining a healthy energy balance	**Behavior change method**	**Practical strategy**
Aw3a. WU are aware of their changed energy expenditure as a result of their illness and wheelchair use.	Consciousness raising (Trans-Theoretical Model)[32,34] Personalize risk and benefits (Health Belief Model)[32,35]	Written information about the consequences of SCI, LLA and a sedentary lifestyle on energy expenditure.
Aw4a. WU describe how varied their current diet is.	Consciousness raising (Trans-Theoretical Model)[32,34] Personalize risk and benefits (Health Belief Model)[32,35] Self-monitoring and Feedback (Social Cognitive Theory)[32,37]	Written messages providing information about the importance of a varied diet and what a varied diet meets. Possibility to keep a food diary. Based on this food diary, computer-tailored feedback is provided on the intake of carbohydrates, fats and proteins.
Aw5a. WU are aware that a healthier diet leads to weight loss or a healthier body composition only if their energy expenditure is higher than their energy intake.	Consciousness raising (Trans-Theoretical Model)[32,34]	Written messages providing information about common causes of unsuccessful weight loss attempts, and conditions that must be met in order to lose weight/improve body composition successfully.
Aw6a. WU are aware of the influence of their social environment on their diet.	Consciousness raising (Trans-Theoretical Model)[32,34] Persuasive communication (Elaboration Likelihood Model)[32,48]	Written messages providing information about risks of not involving the social environment, and arguments to ensure social support in lifestyle change and the maintenance of healthy behavior. Short written messages in the online community. In the face-to-face consultation at the start of the intervention attention is paid to the role that the social environment plays in behavioral change (only applies to blended use of the lifestyle app).

Table 2. Continued from previous page.

Aw7a. WU are aware of situations in which it is difficult to continue eating healthy.	Consciousness raising (Trans-Theoretical Model)[32,34]	Written information and arguments to encourage identifying and anticipating factors that hinder healthy dietary behaviors.
Change objectives aimed at developing and maintaining a healthy balance between exercise and rest/relaxation	**Behavior change method**	**Practical strategy**
Aw1a. WU are aware of their body signals. Aw1b. WU are aware of their body posture. Aw1c. WU describe how they recognize fatigue.	Consciousness raising (Trans-Theoretical Model)[32,34] Personalize risk and benefits (Health Belief Model)[32,35]	Written information and a recorded presentation about body awareness, the causes and consequences of fatigue and recognizing physical and mental signs of fatigue. Exercises to improve body awareness and body posture.
Aw2a. WU are aware of what is demanded from their body and the capacity of their body.	Consciousness raising (Trans-Theoretical Model)[32,34] Personalize risk and benefits (Health Belief Model)[32,35]	Written information and a recorded presentation about balancing body load/demand and capacity to reduce health problems and fatigue. Exercise to gain insight into your own load-capacity balance.
Aw3a. WU are aware of situations that they experience as stressful.	Consciousness raising (Trans-Theoretical Model)[32,34] Personalize risk and benefits (Health Belief Model)[32,35]	Exercise to identify situations that consume and provide physical and mental energy.
Aw4a. WU are aware of the amount of tension in their body. Aw4b. WU are aware of the importance of rest and relaxation for the recovery of their body.	Consciousness raising (Trans-Theoretical Model)[32,34] Active learning (Elaboration Likelihood Model)[32,48]	Written messages and a brochure providing information about the importance of adequate sleep and relaxation for recovery processes. Exercises to improve body awareness.
Aw5a. WU are aware of the influence of sleep on exercise and dietary behavior.	Consciousness raising (Trans-Theoretical Model)[32,34]	Written messages and brochure providing information about the causes and consequences of sleeping problems, and the importance of healthy sleeping habits.

Table 3. Behavior change methods and practical strategies that have been selected to change the **self-efficacy** and **skills** of wheelchair users in order to achieve the change objectives, and with this the intervention goals.

Change objectives aimed at meeting the applicable physical activity and exercise guidelines	Behavior change method	Practical strategy
SeS1a. WU are confident that they can find and understand the applicable physical activity and exercise guidelines. SeS1b. WU show where they can find the applicable physical activity and exercise guidelines.	Facilitation (Social Cognitive Theory)[32,37]	Sharing a pdf and infographic of the physical activity and exercise guidelines for people with a SCI and people with a LLA. Additionally, the guidelines are summarized in short written messages that are shared in an online community group around exercise and physical activity.
SeS3a. WU have confidence that they will be able to be physically active and/or exercise (more often).	Facilitation (Social Cognitive Theory)[32,37] Modeling (Social Cognitive Theory)[32,37]	Exercise database and tailored fitness work-outs that are offered on three levels: beginner, intermediate and advanced. Videos and/or quotes from role models showing that they had to overcome barriers to exercise or become (more) physically active, how they succeeded and how they manage to stay physically active.
SeS4a. WU are confident that they can set realistic physical activity and exercise goals. SeS4b. WU show their action plan.	Facilitation (Social Cognitive Theory)[32,37] Goal setting (Goal-Setting Theory; Theories of Self-Regulation; Health Action Process Approach)[32,38,39]	Providing information and tailored examples of SMART goal setting. Providing a tailored example of an action plan, and a format to facilitate creating your own action plan. Presentation with voice recording explaining how to create an action plan.
SeS5a. WU are confident that they can ask their social environment for help to become and stay physically active.	Planning coping responses (Theories of Self-Regulation; Health Action Process Approach)[32,39]	Exercise to list barriers to physical activity and exercise and to describe how the social environment can support in overcoming these barriers. Online community group in which participants are challenged to share how their social environment supports them to participate in physical and exercise activities.

Table 3. Continued from previous page.

SeS6a. WU are confident that they can identify the exercise and physical activity options in their living environment. SeS6b. WU show the sports and exercise options in their living environment.	Facilitation (Social Cognitive Theory)[32,37]	Information about the role and accessibility of the neighborhood sports coach and sports consultant in adapted sports. Link to national disability sports finder website which enables searching for a sports club by area, sports category, age category and type of impairment.
SeS7a. WU are confident that they can overcome barriers and manage to be more physically active in everyday life.	Planning coping responses (Theories of Self-Regulation; Health Action Process Approach)[32,39] Persuasive communication (Elaboration Likelihood Model)[32,48]	Exercise to list potential barriers to incorporating physical activities into daily life and ways to overcome these barriers. Short written messages providing arguments to maintain a physically active lifestyle in the long term.
SeS8a. WU are confident that they can train their cardiovascular fitness.	Set graded tasks (Social Cognitive Theory; Theories of Self-Regulation; Health Action Process Approach)[32,37,39] Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Exercise database and tailored fitness work-outs including cardiovascular exercises for wheelchair users. These exercises are offered on three levels: beginner, intermediate and advanced. A 3D-animated personal trainer shows the correct performance of each exercise.
Change objectives aimed at meeting the applicable physical activity and exercise guidelines	**Behavior change method**	**Practical strategy**
SeS9a. WU are confident that they can train their muscle strength.	Set graded tasks (Social Cognitive Theory; Theories of Self-Regulation; Health Action Process Approach)[32,37,39] Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Exercise database and tailored fitness work-outs including muscle strengthening exercises for wheelchair users. These exercises are offered on three levels: beginner, intermediate and advanced and are suitable for people with more or less severely impaired arm and/or leg function. A 3D-animated personal trainer shows the correct performance of each exercise.

Table 3. Continued from previous page.

SeS10a. WU are confident that they will be able to keep exercising and stay physically active in difficult situations. SeS10b. WU show their coping plan.	Planning coping responses (Theories of Self-Regulation; Health Action Process Approach)[32,39] Persuasive communication (Elaboration Likelihood Model)[32,48] Facilitation (Social Cognitive Theory)[32,37]	Presentation with voice recording explaining how to overcome potential barriers by creating a coping plan. Providing a tailored example of a coping plan, and a format to facilitate creating your own coping plan.
SeS11a. WU are confident that they can enjoy exercise and physical activity.	Modeling (Social Cognitive Theory)[32,37]	Videos and/or quotes from role models showing that it is possible to find an enjoyable sports or exercise activity and what this has brought them.
SeS12a. WU are confident that they can make a routine of their exercise and physical activity behavior.	Goal setting (Goal-Setting Theory; Theories of Self-Regulation; Health Action Process Approach)[32,38,39] Self-monitoring and Feedback (Social Cognitive Theory)[32,37]	Calendar in which sports and exercise activities can be scheduled. Exercise and physical activity diary that provides insight into the daily exercise and physical activity pattern. Possibility to set exercise and physical activity goals and to keep track of the progress towards achieving these goals.
Change objectives aimed at developing and maintaining a healthy energy balance	**Behavior change method**	**Practical strategy**

Table 3. Continued from previous page.

SeS1a. WU are confident that they can eat healthier.	Facilitation (Social Cognitive Theory)[32,37] Modeling (Social Cognitive Theory)[32,37] Self-monitoring and Feedback (Social Cognitive Theory)[32,37]	Providing a brochure and short written messages with information, tips and tricks regarding adopting and maintaining a healthy diet. Possibility to keep a food diary. Based on this food diary, computer-tailored feedback is provided on the daily calorie intake and intake of carbohydrates, fats and proteins. Providing computer-tailored meal plans based on personal goals. Possibility to exchange healthy recipes. Videos and/or quotes from role models showing that it is possible to adopt and maintain a healthy diet. They tell how they have overcome barriers and what it has brought them.
SeS2a. WU are confident that they can choose healthy food products in the store.	Facilitation (Social Cognitive Theory)[32,37]	Barcode scanner and food product list providing insight into the calories and nutrients in food products.
Change objectives aimed at developing and maintaining a healthy energy balance	**Behavior change method**	**Practical strategy**
SeS3a. WU are confident that they can find out their daily calorie needs. SeS3b. WU are confident that they can adjust their energy intake to their energy expenditure. SeS3c. WU show how they match their energy intake to their energy expenditure. SeS3d. WU will consult a dietician if they need help adjusting their energy intake to their energy consumption.	Facilitation (Social Cognitive Theory)[32,37] Self-monitoring en Feedback (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Personalized advice regarding a healthy daily calorie intake. Possibility to keep a food diary. Based on this food diary, computer-tailored feedback is provided on the daily calorie intake and intake of carbohydrates, fats and proteins. Information about consulting and finding a dietician specializing in SCI or LLA.

Table 3. Continued from previous page.

SeS4a. WU are confident that they can adopt a varied diet. SeS4b. WU show that they can eat varied meals.	Facilitation (Social Cognitive Theory)[32,37] Self-monitoring en Feedback (Social Cognitive Theory)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Providing a brochure and short written messages with information, tips and tricks regarding adopting and maintaining a varied diet. Barcode scanner and food product list providing insight into the nutrients in food products. Possibility to exchange healthy recipes.
SeS6a. WU are confident that their social environment will support them in adjusting their diet.	Planning coping responses (Theories of Self-Regulation; Health Action Process Approach)[32,39]	Exercise to list barriers to adopting and a healthy diet and to describe how the social environment can support in overcoming these barriers. Online community group in which participants are challenged to share how their social environment supports them to eat healthy.
SeS7a. WU are confident that they can maintain a healthy diet. SeS7b. WU show a coping plan.	Planning coping responses (Theories of Self-Regulation; Health Action Process Approach)[32,39] Persuasive communication (Elaboration Likelihood Model)[32,48] Facilitation (Social Cognitive Theory)[32,37]	Presentation with voice recording explaining how to overcome potential barriers by creating a coping plan. Providing a tailored example of a coping plan, and a format to facilitate creating your own coping plan. Providing a brochure and short written messages with information, tips and tricks regarding adopting and maintaining a healthy diet.
Change objectives aimed at developing and maintaining a healthy balance between exercise and rest/relaxation	**Behavior change method**	**Practical strategy**
SeS1a. WU are confident that they can develop good body awareness.	Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Tailored exercises to improve body awareness and body posture.

4

Table 3. Continued from previous page.

SeS2a. WU are confident that they can apply principles related to balancing physical demand and capacity. SeS2b. WU show that they can apply principles related to balancing physical demand and capacity. SeS2c. WU show how they can determine their degree of fatigue.	Active learning (Elaboration Likelihood Model)[32,37] Goal setting (Goal-Setting Theory; Theories of Self-Regulation; Health Action Process Approach)[32,38,39]	Information about applying the "ELCOSICO rules" (ELiminate, Change Order, Simplify, Combine) to save energy during activities and exercises to identify factors that consume and provide energy. Possibility to plan daily activities and schedule time for rest and relaxation. Information on how to use a numeric rating scale and BoWU scale to determine the degree of fatigue.
Change objectives aimed at developing and maintaining a healthy balance between exercise and rest/relaxation	**Behavior change method**	**Practical strategy**
SeS3a. WU are confident that they can influence stressful situations.	Persuasive communication (Elaboration Likelihood Model)[32,48]	Written messages providing information, tips and tricks on how to deal with stressful situations
SeS4a. WU trust they can rest and relax. SeS4b. WU show relaxation exercises.	Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Providing relaxation exercises tailored for wheelchair users with SCI and LLA.
SeS5a. WU are confident that they can develop healthy sleeping habits. SeS5b. WU show that they can apply healthy sleeping habits.	Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Written messages and a brochure tailored to wheelchair users with SCI or LLA providing information, tips and tricks on adopting healthy sleeping habits.

Table 4. Behavior change methods and practical strategies that have been selected to change the **knowledge** of wheelchair users in order to achieve the change objectives, and with this the intervention goals.

Change objectives aimed at meeting the applicable physical activity and exercise guidelines	Behavior change method	Practical strategy
Kn1a. WU describe when they meet the applicable physical activity and exercise guidelines.	Facilitation (Social Cognitive Theory)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Link to PDF files of the scientific exercise guidelines for adults with spinal cord injury and Dutch physical activity guidelines. Written messages and an infographic providing information and arguments to become familiar with the physical activity and exercise guidelines for persons with a SCI or LLA.
Kn2a. WU list the advantages of physical activity and exercise participation.	Persuasive communication (Elaboration Likelihood Model)[32,48] Motivational Interviewing[32,40]	Written messages providing information and arguments to exercise and be physically active. When using the app blended, the lifestyle coach uses motivational interviewing to identify ambivalence to physical activity and exercise participation.
Kn4a. WU name physical activity and exercise activities that match their goals and possibilities. Kn4b. WU formulate SMART physical activity and exercise goals. Kn4c. WU describe what an action plan must meet.	Facilitation (Social Cognitive Theory)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Providing information about sports and exercise activities for wheelchair users and the "Physical Activity Counseling Center" that can help to find a suitable sports and/or exercise activity. Providing a tailored example of an action plan, and a format to facilitate creating your own action plan. Presentation with voice recording explaining the importance of setting SMART goals, and how to create an action plan.
Change objectives aimed at meeting the applicable physical activity and exercise guidelines	**Behavior change method**	**Practical strategy**
Kn6a. WU show where they can find information about suitable exercise and physical activity options in their living environment. Kn6b. WU name suitable sports activities that are offered in and around their place of residence.	Facilitation (Social Cognitive Theory)[32,37]	Information about the role and accessibility of the neighborhood sports coach and sports consultant in adapted sports. Link to national disability sports finder website which enables searching for a sports club by area, sports category, age category and type of impairment.

Table 4. Continued from previous page.

Kn7a. WU name moments in everyday life when they can be more physically active. Kn7b. WU describe how they can increase their level of physical activity in daily life.	Feedback (Social Cognitive Theory)[32,37] Persuasive communication (Elaboration Likelihood Model)[32,48]	Exercise and physical activity diary that provides insight into the daily exercise and physical activity pattern and moments when one could be more physically active. Possibility to link a wrist-worn activity monitor to the app. Written messages providing information and examples of increasing physical activity during daily activities (tiny habits).
Kn8a. WU describe exercises and activities with which they can train their cardiovascular fitness.	Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Written messages providing information and arguments to train cardiovascular fitness. Exercise database and tailored fitness work-outs including cardiovascular exercises for wheelchair users. These exercises are offered on three levels: beginner, intermediate and advanced. A 3D-animated personal trainer shows the correct performance of each exercise.
Kn9a. WU describe the ways in which they can train their muscle strength.	Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Written messages providing information and arguments to train muscle strength. Exercise database and tailored fitness work-outs including muscle strengthening exercises for wheelchair users. These exercises are offered on three levels: beginner, intermediate and advanced and are suitable for people with more or less severely impaired arm and/or leg function. A 3D-animated personal trainer shows the correct performance of each exercise.

Table 4. Continued from previous page.

Kn10a. WU describe strategies to keep exercising regularly in difficult situations. Kn10b. WU describe how to make a coping plan.	Facilitation (Social Cognitive Theory)[32,37] Motivational Interviewing[32,40] Persuasive communication (Elaboration Likelihood Model)[32,48]	Written information and arguments to encourage identifying and anticipating factors that hinder physical activity and exercise. Videos and/or quotes from role models showing that they had to overcome barriers to exercise or become (more) physically active, how they succeeded and how they manage to stay physically active. Presentation with voice recording explaining how to overcome potential barriers by creating a coping plan. Providing a tailored example of a coping plan, and a format to facilitate creating your own coping plan.
Change objectives aimed at meeting the applicable physical activity and exercise guidelines	**Behavior change method**	**Practical strategy**
Kn11a. WU describe sports and exercise activities that they enjoy.	Facilitation (Social Cognitive Theory)[32,37]	Offering / getting acquainted with varied sports and exercise activities through an exercise database and referral to the Physical Activity Counseling Center.
Change objectives aimed at developing and maintaining a healthy energy balance	**Behavior change method**	**Practical strategy**
Kn2a. WU know what healthy food products are.	Facilitation (Social Cognitive Theory)[32,37] Feedback (Social Cognitive Theory)[32,37]	Providing a brochure and short written messages with information, tips and tricks regarding adopting and maintaining a healthy diet. Providing personalized feedback on daily calorie and nutrient intake.

Table 4. Continued from previous page.

Kn3a. WU describe how they can find out and calculate the energy value of foods. Kn3b. WU describe how they match their energy intake to their energy consumption.	Facilitation (Social Cognitive Theory)[32,37] Feedback (Social Cognitive Theory)[32,37]	Possibility to keep a food diary. Based on this food diary, computer-tailored feedback is provided on the daily calorie intake and intake of carbohydrates, fats and proteins. Written information about the consequences of SCI, LLA and a sedentary lifestyle on energy expenditure. Personalized advice regarding a healthy daily calorie intake.
Kn4a. WU describe a healthy and varied diet.	Facilitation (Social Cognitive Theory)[32,37]	Providing a brochure and short written messages with information, tips and tricks regarding adopting and maintaining a healthy, varied diet.
Kn5a. WU describe the potential health consequences of a healthy and unhealthy diet. Kn5b. WU list the conditions for healthy weight loss.	Facilitation (Social Cognitive Theory)[32,37] Motivational Interviewing[32,40]	Written messages providing: information and arguments for the importance of a healthy diet for wheelchair users. information about common causes of unsuccessful weight loss attempts, and conditions that must be met in order to lose weight/improve body composition successfully. When using the app blended, the lifestyle coach uses motivational interviewing to identify ambivalence to healthy food habits.
Kn6a. WU describe how their social environment can support them in adjusting their diet.	Modeling (Social Cognitive Theory)[32,37]	Videos or written stories in which role models explain how their social environment has supported them in achieving a healthy diet. They tell how they got the support they need.

Table 4. Continued from previous page.

Change objectives aimed at developing and maintaining a healthy balance between exercise and rest/relaxation	Behavior change method	Practical strategy
Kn1a. WU know what body awareness is and how they can develop it.	Active learning (Elaboration Likelihood Model)[32,37] Facilitation (Social Cognitive Theory)[32,37]	Written messages providing information and tips for developing good body awareness. Exercises to improve body awareness.
Change objectives aimed at developing and maintaining a healthy balance between exercise and rest/relaxation	**Behavior change method**	**Practical strategy**
Kn2a. WU name principles related to balancing physical load and capacity.	Active learning (Elaboration Likelihood Model)[32,37] Facilitation (Social Cognitive Theory)[32,37]	Written information and a recorded presentation about balancing body load/demand and capacity to reduce health problems and fatigue. Exercise to gain insight into your own load-capacity balance.
Kn3a. WU describe how they can make situations they experience as stressful less stressful.	Facilitation (Social Cognitive Theory)[32,37]	Written messages providing information, tips and tricks on how to deal with stressful situations
Kn5a. WU describe habits that promote sleep.	Facilitation (Social Cognitive Theory)[32,37] Tailoring (Trans-Theoretical Model)[32,34]	Written messages and a brochure tailored to wheelchair users with SCI or LLA providing information, tips and tricks on adopting healthy sleeping habits.

Table 5. Behavior change methods and practical strategies that have been selected to change **the perceived barriers** and **skills** of rehabilitation and lifestyle professionals in order to achieve the change objectives, and with this the intervention goals.

Change objective	Behavior change method	Practical strategy
PB1a. Professionals anticipate barriers to the provision of lifestyle counselling to WU after the rehabilitation phase. S1a. Professionals show how they help WU to formulate and pursue personal lifestyle goals.	Facilitation (Social Cognitive Theory)[32,37] Guided practice (Social Cognitive Theory; Theories of Self-Regulation)[32,37]	Lifestyle app with which rehabilitation and lifestyle professionals can support WU towards an active lifestyle. Meeting in which rehabilitation and lifestyle professionals who use the app exchange experiences.
PB2a. Professionals anticipate factors that prevent them from encouraging WU to comply with the applicable physical activity and exercise guidelines. S2a. Professionals show how they encourage WU to comply with the applicable physical activity and exercise guidelines.	Facilitation (Social Cognitive Theory)[32,37] Guided practice (Social Cognitive Theory; Theories of Self-Regulation)[32,37]	Exercise database and tailored fitness work-outs that can be used to improve the physical activity and fitness of wheelchair users. Meeting in which rehabilitation and lifestyle professionals who use the app exchange experiences.
PB3a. Professionals anticipate barriers that prevent them from encouraging WU to develop and maintain a healthy energy balance. S3a. Professionals show how they encourage WU to develop and maintain a healthy energy balance.	Facilitation (Social Cognitive Theory)[32,37] Guided practice (Social Cognitive Theory; Theories of Self-Regulation)[32,37]	Lifestyle app with which rehabilitation and lifestyle professionals can support WU towards a healthy energy balance. Meeting in which rehabilitation and lifestyle professionals who use the app exchange experiences.
PB4a. Professionals anticipate barriers that prevent them from encouraging WU to develop a healthy balance between exercise and rest/relaxation. S4a. Professionals show how they stimulate WU to develop a healthy balance between exercise and rest/relaxation.	Facilitation (Social Cognitive Theory)[32,37] Guided practice (Social Cognitive Theory; Theories of Self-Regulation)[32,37]	Lifestyle app with which rehabilitation and lifestyle professionals can support WU towards a healthy balance between exercise and rest/relaxation. Meeting in which rehabilitation and lifestyle professionals who use the app exchange experiences.

Table 6. Behavior change methods and practical strategies that have been selected to change the **knowledge** of rehabilitation and lifestyle professionals in order to achieve the change objectives, and with this the intervention goals.

Change objective	Behavior change method	Practical strategy
Kn2a. Professionals describe how WU can comply with the applicable physical activity and exercise guidelines.	Facilitation (Social Cognitive Theory)[32,37]	Manual that describes how the app can be used to guide wheelchair users remotely to an active lifestyle. Information on physical activity and exercise guidelines for wheelchair users. Exercise programs that can be offered to wheelchair users. Exercise database with which tailored exercise programs can be made. Access to the exercise diary, exercise calendar and progress registration of WU.
Kn3a. Professionals describe how WU can develop and maintain a healthy energy balance.	Facilitation (Social Cognitive Theory)[32,37]	Information about the energy expenditure (during rest and physical activities) of wheelchair users. Manual that describes how the app can be used to guide wheelchair users remotely to a healthy energy balance. Possibility to provide WU with nutritional advice via the app (advice contains information about calorie intake and distribution of nutrients) and to offer meal plans and recipes. Possibility to provide WU with information about a healthy and varied diet through the app. Digital food diary based on which feedback can be provided.
Kn4a. Professionals describe how WU can develop a healthy balance between exercise and rest/relaxation.	Facilitation (Social Cognitive Theory)[32,37]	App that offers the possibility to provide WU with information about the development of a healthy balance between exercise and rest/relaxation (information about healthy sleeping habits and balancing load/demand and capacity). Relaxation exercises that can be offered to WU through the app. Possibility to gain insight into the exercise diary of WU so that insight can be obtained into moments when exercise and rest/relaxation are not in balance.

Table 7. Behavior change methods and practical strategies that have been selected to change **the social support** of rehabilitation and lifestyle professionals in order to achieve the change objectives, and with this the intervention goals.

Change objective	Behavior change method	Practical strategy
SS1a. Professionals motivate WU to be physically active, exercise, eat healthy and pay attention to rest/relaxation and healthy sleep habits.	Participation (Organizational Development Theories)[32,49] Facilitation (Social Cognitive Theory)[32,37]	Rehabilitation professionals are included in the planning group that is developing a mobile lifestyle intervention for WU. Rehabilitation and lifestyle professionals have an app at their disposal that they can use to remotely motivate wheelchair users to be physically active, exercise, eat healthy and pay attention to rest/relaxation and healthy sleep habits.
SS2a. Professionals motivate WU to comply with the applicable physical activity and exercise guidelines.	Participation (Organizational Development Theories)[32,49] Facilitation (Social Cognitive Theory)[32,37]	Rehabilitation professionals are included in the planning group that is developing the exercise module of a mobile lifestyle intervention for WU. Rehabilitation and lifestyle professionals have an app at their disposal that they can use to remotely motivate wheelchair users to comply with the applicable physical activity and exercise guidelines.
SS3a. Professionals motivate WU to develop and maintain a healthy energy balance.	Participation (Organizational Development Theories)[32,49] Facilitation (Social Cognitive Theory)[32,37]	Rehabilitation professionals are included in the planning group that is developing the food module of a mobile lifestyle intervention for WU. Dieticians working in the Dutch rehabilitation centers are involved in the development of the nutritional information materials. Rehabilitation and lifestyle professionals have an app at their disposal that they can use to remotely motivate wheelchair users to develop and maintain a healthy energy balance.
SS4a. Professionals motivate WU to develop a healthy balance between exercise and rest/relaxation.	Participation (Organizational Development Theories)[32,49] Facilitation (Social Cognitive Theory)[32,37]	Rehabilitation professionals are included in the planning group that is developing the rest/relaxation module of a mobile lifestyle intervention for WU. Rehabilitation and lifestyle professionals have an app at their disposal that they can use to remotely motivate wheelchair users to develop a healthy balance between exercise and rest/relaxation.

Supplementary appendix 2. Interview guide for the usability and feasibility of the WHEELS project

Topics	Main questions	Possible follow-up questions
Opening	How experienced are you with using smartphone applications?	How long have you been using a smartphone? Which lifestyle related apps do you already use? For what reason do you use these apps?
Goals	What were your goals to work on using the WHEELS app? (e.g. exercising more often, eating healthier, more attention to relaxation)	What is the reason for working on these goals? What was the reason for not working on goals in other lifestyle areas?
Adherence	To what extent have you used the WHEELS app for the entire 12 weeks?	How many times a week? What did you use the WHEELS app for? Which parts? To what extent has the WHEELS app stimulated you to achieve your goals? If not, when did you drop out? What was the reason for that?
Motivation	What has (or has not) helped you to maintain your motivation to change your lifestyle? (personal factors and app related factors)	What went well in this? What did you run into? How did you manage to keep it up?
Ease of use	What came easy to you when it comes to using the app? What was difficult for you when it comes to using the app?	Which aspects of the WHEELS app are unnecessary, could be improved, were unclear? Which aspects of the WHEELS app are useful and clear? Which parts did you expect in the app but were not included?
Satisfaction	What are you satisfied with regarding the app?	Can you give an example? What did you run into that you were not satisfied with? How did you solve that?
Usefulness	To what extent has the app influenced your exercise behavior and/or diet?	How has the app supported you in daily life in the past 12 weeks? To what extent have you achieved your goals? What do you think could be improved about the app?
Ending	Would you recommend the app to others?	Why? Why not?

Supplementary appendix 3. Table S1 – S3

Table S1. Nutritional intake pre and post 12-week intervention based on diet records.

Daily average consumed	Remote-guided (n=5)			Stand-alone (n=5)			All (n=10)			
	Pre, mean (SD)	Post, mean (SD)	P value	Pre, mean (SD)	Post, mean (SD)	P value	Pre, mean (SD)	Post, mean (SD)	P value	Effect size
Kilocalories	2085 (643)	1478 (232)	.043[a]	1755 (392)	1795 (452)	.69[a]	1920 (531)	1637 (377)	.14[a]	.46
Protein (g)	88.0 (16.0)	70.2 (11.0)	.080[a]	71.6 (25.5)	77.9 (15.8)	.23[a]	79.8 (21.8)	74.1 (13.5)	.37	.28
Fat (g)	86.0 (31.0)	60.0 (17.1)	.043[a]	79.8 (35.1)	79.1 (25.6)	.50[a]	82.9 (31.4)	69.6 (22.9)	.07[a]	.56
Carbohydrates (g)	198.6 (80.6)	140.8 (44.6)	.043[a]	161.0 (32.6)	168.5 (80.8)	.69[a]	179.8 (61.3)	154.7 (63.3)	.24[a]	.37
Alcohol (g)	17.5 (15.8)	9.0 (12.4)	.14[a]	8.0 (6.8)	6.8 (10.1)	.72[a]	12.7 (13.3)	7.9 (10.7)	.16[a]	.44
Protein (%)	17.5 (3.3)	19.4 (4.5)	.23[a]	16.3 (4.4)	17.7 (2.9)	.50[a]	16.9 (3.7)	18.6 (3.6)	.14[a]	.47
Fat (%)	36.7 (4.8)	36.1 (6.7)	.69[a]	40.1 (11.5)	40.2 (10.5)	.89[a]	38.4 (8.5)	38.2 (8.6)	.88	.05
Carbohydrates (%)	37.4 (5.8)	37.7 (8.4)	.50[a]	37.9 (10.7)	37.0 (12.9)	.89[a]	37.7 (8.1)	37.3 (10.3)	.88[a]	.05
Alcohol (%)	6.2 (5.7)	4.7 (6.4)	.14[a]	2.7 (2.9)	2.2 (3.2)	.47[a]	4.5 (4.7)	3.4 (5.0)	.09[a]	.53

[a]Indicates non-parametric test used due to violation of normality with corresponding effect size.

Table S2. Body composition changes pre and post 12-week intervention.

Body composition	Remote-guided (n=6)			Stand-alone (n=7)			All (n=13)			
	Pre, mean (SD)	Post, mean (SD)	P value	Pre, mean (SD)	Post, mean (SD)	P value	Pre, mean (SD)	Post, mean (SD)	P value	Effect size
Body mass (kg)	89.2 (20.3)	86.8 (22.9)	.12	77.7 (19.6)	77.1 (18.9)	.24	83.0 (20.0)	81.6 (20.6)	.09	.49
BMI (kg/m^2)	29.2 (5.7)	28.3 (6.3)	.08	30.1 (9.7)	29.9 (9.4)	.13	29.7 (7.8)	29.1 (7.8)	.07	.53
WC (cm)	106.1 (18.3)	101.8 (19.5)	.028	102.1 (8.9)	101.1 (8.1)	.24	103.9 (13.5)	101.4 (13.8)	.015[b]	.76
FM (kg)	35.4 (12.6)	28.0 (12.7)	.028	29.4 (7.4)	25.7 (5.8)	.13	32.1 (10.1)	26.7 (9.2)	.004[b]	.96
FM (%)	39.0 (7.2)	31.2 (8.3)	.028	39.4 (11.7)	35.4 (12.3)	.13	39.2 (9.5)	33.4 (10.5)	.004[b]	.97
FFM (kg)	53.9 (11.4)	58.9 (13.1)	.046	48.3 (18.7)	51.5 (21.4)	.18	50.9 (15.4)	54.9 (17.7)	.023[b]	.70
FFM (%)	61.0 (7.2)	68.8 (8.3)	.028	60.6 (11.7)	64.4 (12.3)	.13	60.8 (9.5)	66.6 (10.5)	.004[b]	.97

[b]Indicates significant difference over time determined by a paired-sample *t* test ($P < .05$).

Abbreviations: BMI = body mass index, WC = waist circumference, FM = fat mass, FFM = fat-free mass.

Table S3. Results from questionnaires pre and post 12-week intervention.

Questionnaire Pre, mean (SD)	Remote-guided (n=4) Post, mean (SD)	P value	Pre, mean (SD)	Stand-alone (n=8) Post, mean (SD)	P value	Pre, mean (SD)	All (n=12) Post, mean (SD)	P value	Effect size	
PASIPD (MET h/day)	28.5 (18.4)	26.58 (13.4)	>.99	21.5 (14.0)	20.2 (11.9)	.78	23.8 (15.1)	22.4 (12.2)	.64	.14
GSES	31.8 (5.6)	32.5 (4.8)	.28	35.3 (3.4)	34.1 (4.1)	.53	34.1 (4.3)	33.6 (4.2)	.69	.11
ESES	31.5 (4.3)	29.8 (5.9)	.36	33.9 (3.6)	33.8 (3.2)	.72	33.0 (3.8)	32.4 (4.4)	.50[a]	.07
CIS20R	77.0 (15.3)	72.0 (12.8)	.11	70.0 (9.6)	68.4 (4.2)	.58	72.3 (11.6)	69.6 (7.7)	.18[a]	.39
PSQI	7.8 (3.2)	6.5 (2.6)	.10	8.1 (2.7)	6.8 (2.2)	.18	8.0 (2.7)	6.7 (2.2)	.06	.57
SF-36E										
Physical functioning	43.8 (16.5)	47.5 (8.7)	.46	56.3 (19.2)	50.0 (22.0)	.35	52.1 (18.6)	49.2 (18.2)	.58	.16
Social functioning	68.8 (7.2)	78.1 (15.7)	.18	75.0 (21.1)	79.7 (24.0)	.60	72.9 (17.5)	79.2 (20.9)	.36[a]	.27
Role limitation physical	53.1 (19.4)	48.4 (14.8)	.71	60.2 (29.9)	64.8 (17.7)	.80	57.8 (26.1)	59.4 (18.0)	.84	.06
Role limitation emotional	66.7 (26.4)	70.8 (19.8)	.85	85.4 (21.2)	76.0 (28.0)	.18	79.2 (23.7)	74.3 (24.7)	.53[a]	.18
Mental health	82.5 (15.0)	73.8 (13.8)	.10	81.3 (12.5)	75.0 (16.7)	.55	81.7 (12.6)	74.6 (15.1)	.13	.46
Energy/vitality	59.4 (13.0)	56.3 (8.8)	.41	64.1 (15.9)	65.6 (12.9)	.94	62.5 (14.6)	62.5 (12.2)	>.99	<.01
Pain	59.2 (19.9)	56.6 (23.9)	>.99	58.9 (17.8)	45.4 (20.8)	.046	59.0 (17.6)	49.1 (21.5)	.11	.48
General health perceptions	55.0 (18.3)	50.0 (16.8)	.46	68.1 (17.5)	65.0 (22.5)	.55	63.8 (18.1)	60.0 (21.3)	.37[a]	.26

[a]Indicates non-parametrical test used due to violation of normality.

Abbreviations: PASIPD = Physical Activity Scale for individuals with Physical Disability, GSES = General Self-Efficacy Scale, ESES = Exercise Self-Efficacy Score, CIS20R = Checklist Individual Strength, PSQI = Pittsburgh Sleep Quality Index, SF36E = Short Form Health Survey Enabled 36.

References

1. Green LW, Kreuter MW. Health Program Planning: An Educational and Ecological Approach. 4th ed. New York: McGraw-Hill Higher Education; 2005.
2. Van Den Berg-Emons RJ, Bussmann JB, Stam HJ. Accelerometry-based activity spectrum in persons with chronic physical conditions. Arch Phys Med Rehabil 2010;91(12):1856–1861.
3. Miller MJ, Jones J, Anderson CB, Christiansen CL. Factors influencing participation in physical activity after dysvascular amputation: a qualitative meta-synthesis. Disabil Rehabil 2019;41(26):3141–3150.
4. RIVM. Beweegrichtlijnen. 2019 [cited 2020 May 13]. Available from: https://www.sportenbewegenincijfers.nl/kernindicatoren/beweegrichtlijnen
5. RIVM. Sportdeelname wekelijks. 2019 [cited 2020 May 13]. Available from: https://www.sportenbewegenincijfers.nl/kernindicatoren/sportdeelname-wekelijks%0D
6. Buman MP, Winkler EAH, Kurka JM, Hekler EB, Baldwin CM, Owen N, Ainsworth BE, Healy GN, Gardiner PA. Reallocating time to sleep, sedentary behaviors, or active behaviors: Associations with cardiovascular disease risk biomarkers, NHANES 2005-2006. Am J Epidemiol 2014;179(3):323–334.
7. Martin Ginis KA, van der Scheer JW, Latimer-Cheung AE, Barrow A, Bourne C, Carruthers P, Bernardi M, Ditor DS, Gaudet S, de Groot S, Hayes KC, Hicks AL, Leicht CA, Lexell J, Macaluso S, Manns PJ, McBride CB, Noonan VK, Pomerleau P, Rimmer JH, Shaw RB, Smith B, Smith KM, Steeves JD, Tussler D, West CR, Wolfe DL, Goosey-Tolfrey VL. Evidence-based scientific exercise guidelines for adults with spinal cord injury: an update and a new guideline. Spinal Cord 2018;56(4);308-321. [doi: 10.1038/s41393-017-0017-3]
8. Beweegrichtlijn. [cited 2020 Jun 26]. Available from: https://www.dwarslaesie.nl/dagelijks-leven/gezondheid/bewegen/
9. Lieberman J, Goff D, Hammond F, Schreiner P, Norton HJ, Dulin M, Zhou X, Steffen L. Dietary intake relative to cardiovascular disease risk factors in individuals with chronic spinal cord injury: A pilot study. Top Spinal Cord Inj Rehabil 2014;20(2):127–136.
10. Tomey KM, Chen DM, Wang X, Braunschweig CL. Dietary intake and nutritional status of urban community-dwelling men with paraplegia. Arch Phys Med Rehabil 2005;86(4):664–671. [doi: 10.1016/j.apmr.2004.10.023]
11. Westerkamp EA, Strike SC, Patterson M. Dietary intakes and prevalence of overweight/obesity in male non-dysvascular lower limb amputees. Prosthet Orthot Int 2019;43(3):284–292. [doi: 10.1177/0309364618823118]
12. Giannoccaro MP, Moghadam KK, Pizza F, Boriani S, Maraldi NM, Avoni P, Morreale A, Liguori R, Plazzi G. Sleep disorders in patients with spinal cord injury. Sleep Med Rev 2013;17(6):399–409. [doi: 10.1016/j.smrv.2012.12.005]
13. Fogelberg DJ, Leland NE, Blanchard J, Rich TJ, Clark FA. Qualitative experience of sleep in individuals with spinal cord injury. OTJR Occup Particip Heal 2017;37(2):89–97. [doi: 10.1177/1539449217691978]
14. Pell JP, Donnan PT, Fowkes FG, Ruckley C V. Quality of life following lower limb amputation for peripheral arterial disease. Eur J Vasc Surg 1993;7(4):448–451.
15. Jensen MP, Truitt AR, Schomer KG, Yorkston KM, Baylor C, Molton IR. Frequency and age effects of secondary health conditions in individuals with spinal cord injury: A scoping review. Spinal Cord 2013;51(12):882–892. [doi: 10.1038/sc.2013.112]
16. Post MWM, Van Leeuwen CMC. Psychosocial issues in spinal cord injury: A review. Spinal Cord 2012;50(5):382–389. [doi: 10.1038/sc.2011.182]

17. Mckechnie PS, John A. Anxiety and depression following traumatic limb amputation: A systematic review. Injury 2014;45(12):1859–1866.

18. Nooijen CFJ, Vogels S, Bongers-Janssen HMH, Bergen MP, Stam HJ, Van Den Berg-Emons HJG. Fatigue in persons with subacute spinal cord injury who are dependent on a manual wheelchair. Spinal Cord 2015;53(10):758–762. [doi: 10.1038/sc.2015.66]

19. Wong S, Kenssous N, Hillier C, Pollmer S, Jackson P, Lewis S, Saif M. Detecting malnutrition risk and obesity after spinal cord injury: a quality improvement project and systematic review. Eur J Clin Nutr 2018;72(11):1555–1560. [doi: 10.1038/s41430-018-0194-y]

20. Wen H, DeVivo MJ, Mehta T, Baidwan N, Chen Y. The impact of body mass index on one-year mortality after spinal cord injury. J Spinal Cord Med 2019; [doi: 10.1080/10790268.2019.1688021]

21. Ravenek KE, Ravenek MJ, Hitzig SL, Wolfe DL. Assessing quality of life in relation to physical activity participation in persons with spinal cord injury: A systematic review. Disabil Health J 2012;5(4):213–223. [doi: 10.1016/j.dhjo.2012.05.005]

22. Christensen J, Ipsen T, Doherty P, Langberg H. Physical and social factors determining quality of life for veterans with lower-limb amputation(s): a systematic review. Disabil Rehabil 2016;38(24):2345–2353.

23. van den Akker LE, Holla JFM, Dadema T, Visser B, Valent LJ, de Groot S, Dallinga JM, Deutekom M. Determinants of physical activity in wheelchair users with spinal cord injury or lower limb amputation: perspectives of rehabilitation professionals and wheelchair users. Disabil Rehabil 2019;0(0):1–8. [doi: 10.1080/09638288.2019.1577503]

24. Holla JFM, van den Akker LE, Dadema T, de Groot S, Tieland M, Weijs PJM, Deutekom M. Determinants of dietary behaviour in wheelchair users with spinal cord injury or lower limb amputation: Perspectives of rehabilitation professionals and wheelchair users. PLoS One 2020;15(1):1–19. [doi: 10.1371/journal.pone.0228465]

25. Martin Ginis KA, Ma JK, Latimer-Cheung AE, Rimmer JH. A systematic review of review articles addressing factors related to physical activity participation among children and adults with physical disabilities. Health Psychol Rev 2016;10(4):478–494. [doi: 10.1080/17437199.2016.1198240]

26. Kooijmans H, Post M, Motazedi E, Spijkerman D, Bongers-Janssen H, Stam H, Bussman H. Exercise self-efficacy is weakly related to engagement in physical activity in persons with long-standing spinal cord injury. Disabil Rehabil 2019;1–7. [doi: 10.1080/09638288.2019.1574914]

27. Littman AJ, Boyko EJ, Thompson M Lou, Haselkorn JK, Sangeorzan BJ, Arterburn DE. Physical activity barriers and enablers in older Veterans with lower-limb amputation. 2014;51(6):895–906. [doi: 10.1682/JRRD.2013.06.0152]

28. Martin Ginis KA, Latimer AE, Arbour-Nicitopoulos KP, Bassett RL, Wolfe DL, Hanna SE. Determinants of physical activity among people with spinal cord injury: A test of social cognitive theory. Ann Behav Med 2011;42(1):127–133. [doi: 10.1007/s12160-011-9278-9]

29. Crawford DA, Hamilton TB, Dionne CP, Day JD. Barriers and facilitators to physical activity participation for men with transtibial osteomyoplastic amputation: A thematic analysis. J Prosthetics Orthot 2016;28(4):165–172. [doi: 10.1097/JPO.0000000000000109]

30. Phang SH, Martin Ginis KA, Routhier F, Lemay V. The role of self-efficacy in the wheelchair skills-physical activity relationship among manual wheelchair users with spinal cord injury. Disabil Rehabil 2012;34(8):625–632. [doi: 10.3109/09638288.2011.613516]

31. Fernandez ME, ten Hoor GA, van Lieshout S, Rodriguez SA, Beidas RS, Parcel G, Ruiter RAC, Markham CM, Kok G. Implementation mapping: Using intervention mapping to develop implementation strategies. Front Public Heal 2019;7(JUN):1–15. [doi: 10.3389/fpubh.2019.00158]

32. Bartholomew LK, Markham CM, Ruiter RAC, Fernandez ME, Kok G, Parcel GS. Planning health promotion programs: an intervention mapping approach. 4th ed. San Fransisco: Jossey-Bass; 2016.

33. Brug J, van Assema P, Lechner L. Gezondheidsvoorlichting en gedragsverandering: een planmatige aanpak. 9e ed. Assen: Koninklijke van Gorcum BV.; 2017.

34. Prochaska JO, Redding CA, Evers KE. The transtheoretical model and stages of change. In: Glanz K, Rimer BK, Viswanath K, editors. Heal Behav Heal Educ theory, Res Pract 4th ed San Fransisco, CA: Jossey-Bass; 2008. p. 98–120.

35. Champion VL, Skinner CS. The health belief model. In: Glanz K, Rimer BK, Viswanath K, editors. Heal Behav Heal Educ Theory, Res Pract 4th ed San Fransisco, CA: Jossey-Bass; 2008. p. 45–65.

36. Petty RE, Barden J, Wheeler SC. The elaboration likelihood model of persuasion: health promotions that yield sustained behavioral change. In: DiClemente RJ, Crosby RA, Kegler MC, editors. Emerg Theor Heal Promot Pract Res Strateg Improv public Heal 1st ed San Fransisco, CA: Jossey-Bass; 2002. p. 71–99.

37. McAlister AI, Perry CI, Parcel GS. How individuals, environments, and health behaviors interact: Social Cognitive Theory. In: Glanz K, Rimer BK, Viswanath K, editors. Heal Behav Heal Educ theory, Res Pract 4th ed San Fransisco, CA: Jossey-Bass; 2008. p. 169–187.

38. Latham GP, Locke EA. New developments in and directions for goal-setting research. Eur Psychol 2007;12(4):290–300.

39. Schwarzer R, Lippke S, Luszcynska A. Mechanisms of health behavior change in persons with chronic illness or disability: the Health Action Process Approach (HAPA). rehabilition Psychol 2011;56(3):161–170.

40. Miller WR, Rollnick S. Motivational Interviewing: helping people change. 3rd ed. New York: The Guildford press; 2013.

41. Oinas-Kukkonen H, Harjumaa M. Persuasive systems design: Key issues, process model, and system features. Commun Assoc Inf Syst 2009;24(1):485–500. [doi: 10.17705/1cais.02428]

42. Riebe D, Ehman JK, Liguori G, Magal M, American College of Sports Medicine. ACSM's guidelines for exercise testing and prescription. 10th ed. New York: Wolters Kluwer; 2018.

43. Health Council of the Netherlands. Dutch physical activity guidelines 2017. The Hague; 2017.

44. Voedingscentrum. Gezond eten. [cited 2020 May 14]. Available from: https://www.voedingscentrum.nl/nl/gezond-eten-met-de-schijf-van-vijf.aspx

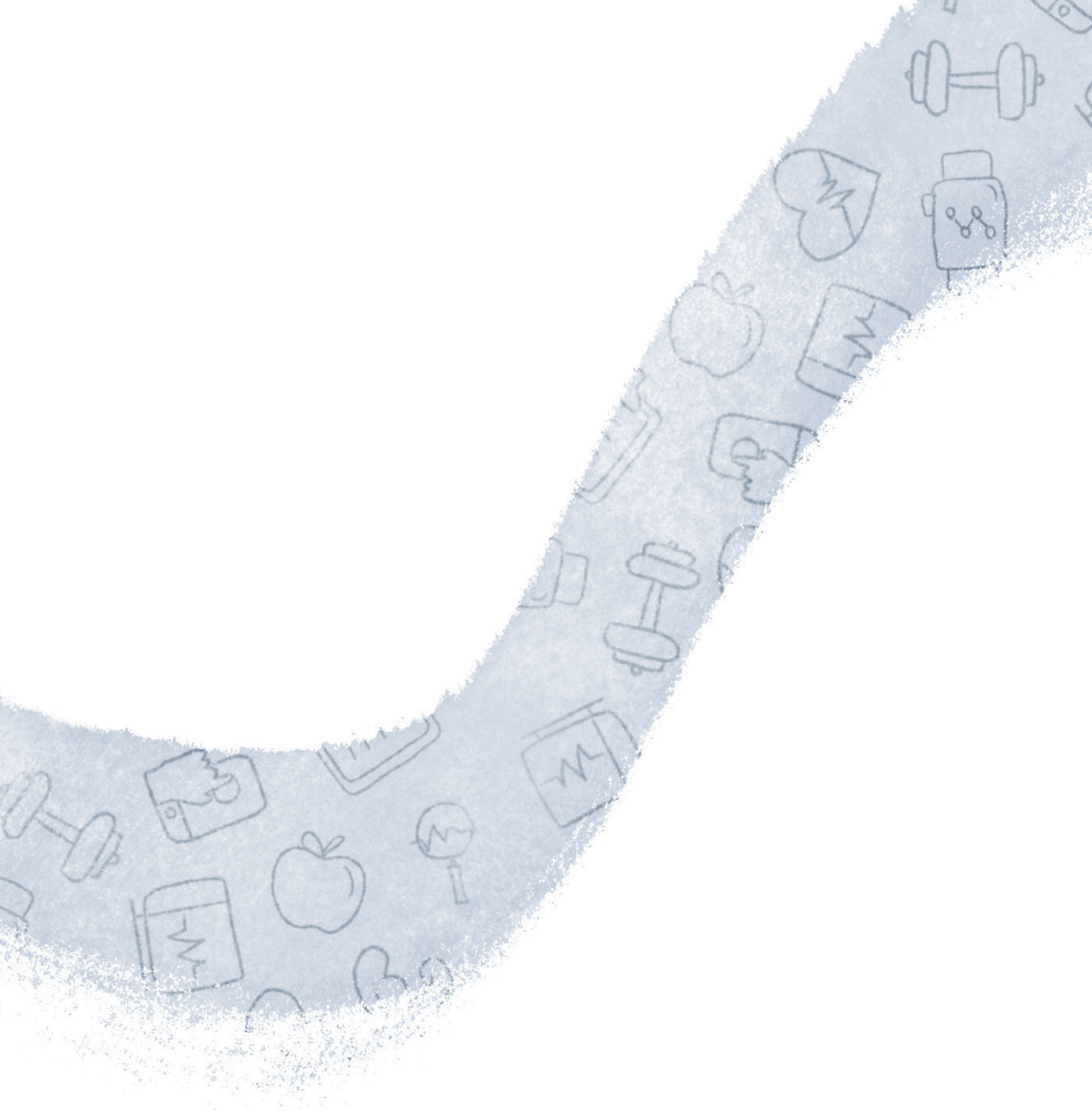
45. Lagerström A-C, Wahman K. The art of healthy living with physical impairments. Available from: http://spinalis.se/wp-content/uploads/2015/05/The-art-of-healthy-living-with-physical-impairments.pdfISBN:9789186939588

46. Fleuren MAH, Paulussen TGWM, Dommelen P, Buuren S Van. Towards a measurement instrument for determinants of innovations. Int J Qual Heal Care 2014;26(5):501–510. [doi: 10.1093/intqhc/mzu060]

47. Fernandez ME, Ruiter RAC, Markham CM, Kok G. Intervention mapping: Theory-and evidence-based health promotion program planning: Perspective and examples. Front Public Heal 2019;7(209). [doi: 10.3389/fpubh.2019.00209] PMID:31475126

48. Petty RE, Barden J, Wheeler SC. The elaboration likelihood model of persuasion: health promotions that yield sustained behavioral change. In: DiClemente RJ, Crosby RA, Kegler MC (Eds.), Emerging theories in health promotion practice and research: strategies for improving public health (p. 71-99). 1st ed. San Francisco, CA: Jossey-Bass. 2002.

49. Cummings TG, Worley CG. Organization Development & Change. 9th ed. Mason, OH: South-Western Cengage Learning. 2009.



Chapter 5

Lifestyle and Health Changes in Wheelchair Users with a Chronic Disability after 12 Weeks of Using the WHEELS mHealth Application

Published as: Hoevenaars D, Holla JFM, de Groot S, Weijs PJM, Kraaij W, Janssen TWJ. Lifestyle and Health Changes in Wheelchair Users with a Chronic Disability after 12 Weeks of Using the WHEELS mHealth Application. Disability and Rehabilitation: Assistive Technology 2022.

Abstract

Purpose: To determine changes in physical activity, nutrition, sleep behaviour and body composition in wheelchair users with a chronic disability after 12 weeks of using the WHEELS mHealth application (app).

Methods: A 12-week pre-post intervention study was performed, starting with a 1-week control period. Physical activity and sleep behaviour were continuously measured with a Fitbit charge 3. Self-reported nutritional intake, body mass and waist circumference were collected. Pre-post outcomes were compared with a paired-sample t-test or Wilcoxon signed-rank test. Fitbit data were analysed with a mixed model or a panel linear model. Effect sizes were determined and significance was accepted at $p < .05$.

Results: Thirty participants completed the study. No significant changes in physical activity (+1.5 √steps) and sleep quality (-9.7 sleep minutes; -1.2% sleep efficiency) were found. Significant reduction in energy (-1022 kJ, $d = 0.71$), protein (-8.3 g, $d = 0.61$) and fat (-13.1 g, $d = 0.87$) intake, body mass (-2.2 kg, $d = 0.61$) and waist circumference (-3.3 cm, $d = 0.80$) were found.

Conclusion: Positive changes were found in nutritional behaviour and body composition, but not in physical activity and sleep quality. The WHEELS app seems to partly support healthy lifestyle behaviour.

Keywords: mHealth; wheelchair user; lifestyle; intervention; mobile health; chronic disability

Introduction

Obesity rates have been growing rapidly worldwide over the last decades, making it an increasing global health problem as it is strongly associated with multiple chronic diseases such as cardiovascular disease, diabetes, and different forms of cancer [1]. With the increasing obesity rates, healthcare expenditure has globally risen as well [2], partly caused by lifestyle diseases. The high prevalence of obesity is mainly caused by relative low physical activity levels combined with poor nutrition choices and thus high energy intake, causing an imbalance in energy expenditure and energy intake [3]. However, additional factors such as sleep duration have shown to be associated with obesity and weight gain as well and should, therefore, also be taken into account and targeted together with physical activity and nutrition [4]. Individuals with chronic disabilities show relatively high obesity rates [5], making them a vulnerable group for lifestyle-related diseases.

Lifestyle-related diseases are non-infectious diseases that tend to develop over a longer period of time due to a combination of behavioural, genetic, physiological and environmental factors [6]. Risk factors for lifestyle-related diseases are partly modifiable by influencing behaviour. Health promotion by focusing on behaviour change can be successfully applied in various ways. Mobile health (mHealth) is a rapidly growing mode of delivery that has shown its potential for behaviour change in previous research [7–9], and removes potential barriers for individuals with restricted mobility such as wheelchair users. Multicomponent interventions have shown superior results compared to single component interventions [10,11]. Although, numerous multicomponent lifestyle applications (apps) exist, none are designed with and for wheelchair users. Therefore, the WHEELS lifestyle app was developed specifically for and together with wheelchair users to promote and support a healthy lifestyle on the aspects physical activity, nutrition and sleep & relaxation [12].

The WHEELS app was developed using the intervention mapping protocol [13], based on behaviour change theories and evidence based methods [14–19]. The goal of combining these methods within the app was to provide the necessary tools at each stage of the transtheoretical model [15], to achieve a shift towards healthier behaviour on the aspects physical activity, nutrition and sleep & relaxation. According to the transtheoretical model, individuals shift between different stages during behaviour change (precontemplation, contemplation, determination, action, relapse and maintenance), to eventually adapt and maintain a new learned behaviour. Therefore, one could argue that a stage shift towards maintenance is likely associated with changes in physical activity and nutritional intake. To a lesser extent this might be applicable for sleep quality, as this is harder to influence by behaviour than physical activity and nutritional intake.

A pilot study on the usability and feasibility of the WHEELS app showed promising results for behaviour and health change, with a tendency to favorable results for the remote-guided group. The app showed room for improvement on usability and seemed feasible to deploy on a larger scale [12]. Due to a small sample size, limited significant improvements were registered in the pilot study on outcome measures for lifestyle and health. Based on the feedback from the study participants, in-app navigation was improved, and a Fitbit integration was added with wheelchair-specific energy estimates. In addition, a lifestyle coach was added for in-app support. The objectives of this study were: (1) to evaluate if using the WHEELS app leads to changes in lifestyle regarding physical activity, nutrition, sleep behaviour, body composition and secondary lifestyle and health-related outcomes; and (2) to explore whether an experienced shift in stage of change (SoC) is related to actual behaviour change in relatively inactive wheelchair users with a chronic disability.

Methods

Study Design and Participants

Wheelchair users were asked to participate in a 12-week intervention study with a pre-post design, focusing on improving their lifestyle with the help of a lifestyle app, including a 1-week control period prior to the intervention period. The study was performed during the global Covid-19 pandemic, restricting possibilities for physical measurements. Therefore, all collected data were self-reported and collected from a distance. Recruitment of participants took place by advertisements at patients' associations, on social media, websites, magazines and within the rehabilitation centre Reade in Amsterdam. Individuals were eligible to participate if the following inclusion criteria were met: manual wheelchair user; wheelchair use for longer distances (>500m); 18 to 75 years old; access to a smartphone or tablet; sufficient knowledge of the Dutch language to understand the content of the app and the study, not meeting the spinal cord injury (SCI) exercise guidelines for cardiometabolic health [20]. Potential participants were excluded if one or more of the following exclusion criteria were met: insufficient understanding of technology to benefit from the app; insufficient functioning of arm/hand to operate a smartphone or tablet; presence of progressive disorders that could influence the outcomes; presence of psychiatric disorders; negative advice regarding unsupervised exercise based on the Lausanne recommendations [21]. A sample size calculation, performed with Gpower [22], indicated that a minimum of 27 participants was needed based on a repeated measures design including 4 measurement occasions with an effect size of 0.14 [23,24], an ICC of 0.90 of the Fitbit [25] and with an α of 0.05 and a β of 0.95. Taking a 10% dropout into account resulted in a desired sample size of at least 30 participants. All participants provided written informed consent and ethical approval was given by the local Medical Ethical Committee of Erasmus MC (MEC-2019-0826).

Procedure

At the start of the study, participants were asked to start wearing a Fitbit Charge 3 activity tracker at the wrist. After a 1-week control period, participants received access to the WHEELS lifestyle app and were asked to improve their lifestyle with the help of the app during the following 12 weeks. The WHEELS app is targeted to help wheelchair users comply with scientific exercise guidelines for adults with SCI [20], achieve a healthy energy balance, and achieve a healthy balance between exercise and sleep/relaxation [12]. Data from the Fitbit were continuously collected throughout the study period as shown in figure 1. Nutrition diaries were administered during the first intervention week and after the intervention period. Online questionnaires and body composition measurements were self-administered during the control week and after the final week of the intervention period.

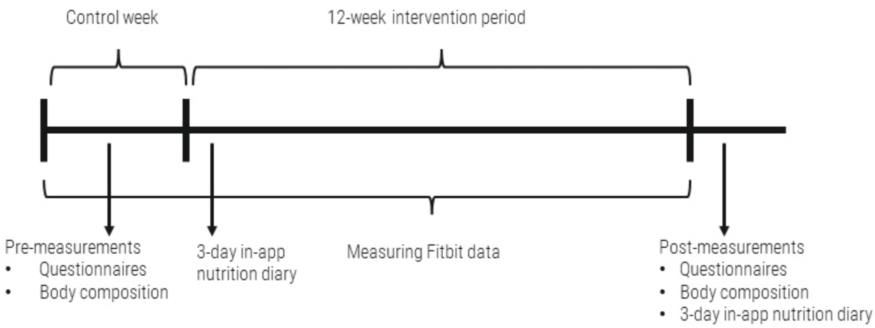


Figure 1. Schematic overview of the study protocol.

Intervention

The intervention provided during the 12-week period consisted of the WHEELS wheelchair-specific mHealth lifestyle app. This app focuses on three aspects: physical activity, nutrition and sleep & relaxation. Information, tips, tricks and feedback are presented in the app on these three aspects combined with exercises that can be performed in the wheelchair, a nutrition plan and tools to achieve behaviour change. The nutrition plan was personalised based on personal characteristics (sex, age and body mass) and the participant's goal. Participants were able to log their progress, get in contact with other users in the community section and schedule workouts in their calendar. The developmental process, content and available functions of this app were described in a previous published paper [12]. On top of the earlier described app functions, the possibility of a smartwatch integration was added to provide the user objective real time feedback on physical activity, energy expenditure and sleep.

The nutrition part of the app included an energy balance overview, starting each day with a person specific target for daily energy and nutrition intake based on an estimate of their basal metabolic rate. The basal metabolic rate was determined by the Schofield equation [26] and based on the personal characteristics: sex, age and body mass. This outcome was subsequently converted with a factor 0.85. This factor was determined based on a comparison of our own unpublished data and studies in which the basal metabolic rate of individuals with and without SCI was measured. In these studies, individuals with SCI showed approximately a factor of 0.85 in basal metabolic rate compared to able-bodied participants [27,28]. The basal metabolic rate was supplemented throughout the day with the accumulated activity energy expenditure estimated by the Fitbit. When individuals set a goal other than maintaining body mass (either loose or gain weight) an energy deficit or surplus was included in their daily starting value. Depending on the amount of weight loss/increase target and the time period in which this target was set, a larger or smaller correction was applied to the daily starting value.

During the study participants wore a Fitbit Charge 3 wrist worn activity tracker. Estimated energy expenditure data from the Fitbit on physical activity performed during the day was imported in the WHEELS app and converted with a factor of 0.77 into a more realistic calorie count of performed activities, which fitted better to the wheelchair community. Previous research suggests one metabolic equivalent (MET) for individuals with SCI should be adjusted to 2.7 $mL \cdot kg^{-1}min^{-1}$, which is a factor of 0.77 compared to 3.5 $mL \cdot kg^{-1}min^{-1}$ for abled-bodied individuals [29]. The accumulated energy expenditure during the day was presented real in time within the app and summed with their personal daily starting value. The energy expenditure overview could be compared to the registered energy intake when the participant logged their nutrition intake, providing an overview of their daily energy balance.

During the intervention period, users could consult a lifestyle coach within the app with any questions regarding lifestyle, app functionalities or other topics related to the intervention study. In additional to answering questions, the coach provided information, tips and tricks on exercise, nutrition, sleep and relaxation on a weekly basis in the community part of the app throughout the 12-week intervention. Additionally, minor changes were made prior to the intervention on the in-app navigation of the single exercise and exercise program search functions to improve usability, based on feedback received during the pilot study.

Outcome Measures

Stage of Change

The transtheoretical model of change was used pre and post-intervention to measure possible shifts in SoC of the individual in adopting healthy physical activity and nutritional behaviour [30]. Participants were asked whether they were currently meeting the SCI exercise guidelines for cardiometabolic health [20] and if they were eating according to the Dutch national nutrition guidelines from the Netherlands Nutrition Centre [31]. Participants could answer on each of these questions with one the following statements: (1) no intention to change behaviour (pre-contemplation); (2) intention to change within next 6 months (contemplation stage); (3) intention to change within the next 30 days (preparation); (4) lifestyle modifications are made for fewer than 6 months (action stage); (5) working to prevent relapse and consolidate gains (maintenance).

Fitbit Data

The Fitbit Charge 3 (Fitbit inc., San Francisco, USA, software versions 3.42.1 - 3.45.1 2021, firmware version 28.20001.88.11) is a commercially available wrist-worn activity tracker released in 2018. The Charge 3 uses a variety of sensors, including a 3-axial accelerometer, an optical heart-rate tracker and an altimeter. The Fitbit was used to continuously measure lifestyle-related outcomes during the control and intervention period. Data were collected on the aspects physical activity ('steps') and sleep (sleep minutes and sleep efficiency). Previous research has shown that using the registered 'steps' of a Fitbit allows for detecting changes in activity levels during wheelchair activities in individuals with SCI [32]. The Fitbit was used to register 'steps' accumulated over a day and provided insight into participants' total daily activity level. The Fitbit was used to register time awake and time asleep and used these outcomes to determine sleep efficiency expressed in percentage and total sleep time in minutes. The Fitbit Charge 3 is able to register sleep behaviour based on a combination of registered movement and heart rate patterns [33]. It was shown that the Fitbit can accurately measure sleep time and sleep onset latency, allowing a valid sleep efficiency measurement in a free-living environment [34]. During this study, all Fitbit's push notifications, except for the low-battery notification, were disabled to limit the intervention effect of the activity tracker. The users Fitbit account was linked with a Sport Data Valley (LIACS, Universiteit Leiden, Leiden, The Netherlands) account, a platform that allows the users and researchers to easily store, manage, share and analyse data anonymously.

The minimum awake wear time to determine if a day was valid to use for analysis was set at 12 hours a day. This was done to ensure a valid representation of physical activity with the recommended awake wear time of at least 10 hours [35]. In case of sleep data, registered sleep with a minimum sleep time of 3 hours was considered a valid recorded sleep period. A minimum of 4 valid days/nights, of which at least one weekend day/night, was necessary to construct a valid weekly average of a Fitbit outcome measure for both physical activity and sleep [36]. These were used to construct intervention period averages to test changes over time. A total of 4 intervention period averages were constructed, i.e., control period (week average of the control week prior the start of the intervention), start (average of available week averages of intervention week 1 – 4), middle (intervention week 5 – 8) and end intervention period (intervention week 9 – 12).

Nutrition

Participants received instructions on how to log their nutritional intake and were asked to do this for 3 consecutive days with one weekend day in the WHEELS lifestyle app twice, at the start and after the intervention period. This method is considered a reliable method for dietary assessment [37]. The app allowed users to log meals and products in the app connected to a large nutrition database, providing information on energy and the macronutrients carbohydrates, protein and fat. Uncertainties about registered diet records (i.e., unrealistic food proportions, incomplete days) were solved by contacting the participant. Diet records were analysed based on nutrition values averaged over the 3 available valid days.

Body Composition

Body mass and waist circumference were collected pre and post-intervention, if possible. Participants were asked to measure their body mass, up to 1 decimal, in the morning before breakfast, when the necessary weighing equipment was available. All participants received a tape measure at inclusion and were asked to measure their waist circumference three times at the level of umbilicus in supine position up to 0.5 cm accuracy during a regular exhale. The average of three waist circumference measurements was used as the outcome. BMI (body mass / height^2) was calculated using self-reported height if the participant was able to measure body mass. In case of a lower-limb amputation, the relative segmental mass of the amputated limb was determined by the formula of Osterkamp [38] and adjusted for lost body mass to calculate BMI according to the formula of Himes [39].

Questionnaires

Questionnaires were administered online in Qualtrics (Provo, Utah, USA) in which personal and demographic (sex, age, height, educational level), disability-related characteristics and personal intervention goals were asked, on top of the below stated questionnaires. Educational level was divided into lower, middle and higher educational level according to the Dutch central agency for statistics [40]. SCI was divided into tetraplegia (neurological lesion at or above T1) or paraplegia (neurological lesion below T1).

Physical Activity. The Dutch Physical Activity Scale for Individuals with Physical Disabilities (PASIPD), a 12-item 7-day recall self-reported questionnaire to evaluate the physical activity level in individuals with a physical disability, was administered. The PASIPD outcome is the number of metabolic equivalents of task (MET) hours spent per day calculated according to the method of Washburn [41]. The score in METS can range from 0 to 182.3.

Body Satisfaction. The adult body satisfaction questionnaire was used to measure perceived body satisfaction [42]. The questionnaire contains 10 items with 7-point Likert scale answer options, ranging from -3 to 3. The scores on the items are divided and averaged over the 2 subscales, function (7 items) and appearance (3 items), where a higher score represents a higher body satisfaction.

Exercise Self-Efficacy. The Exercise Self-Efficacy Scale (ESES) is a valid and reliable 10-item questionnaire which was used to assess exercise self-efficacy [43,44]. The questionnaire contains 4-point Likert scale answer options with a total score ranging from 10 to 40, where a higher score represents a higher exercise self-efficacy.

Fatigue. The Checklist Individual Strength (CIS20R) questionnaire was used to measure fatigue. This self-reported questionnaire consists of 20 questions with a 7-point Likert scale answer option, providing a total score between 20 and 140, with a higher score representing a more severe experienced fatigue. The questionnaire is considered as a suitable and reliable method to measure fatigue [45,46].

Sleep Quality. The Pittsburgh Sleep Quality Index (PSQI) was administered, which is considered as a valid self-reported questionnaire to evaluate sleep quality [47,48]. The questionnaire consists of 7 component scores based on 19 items, resulting in a total score range of 0 – 21, with a higher score representing worse sleep quality.

Quality of Life. Health-related quality of life on eight different dimensions was measured with the Dutch Short Form Health survey Enabled (SF-36E) questionnaire, considered a reliable and valid questionnaire [49,50]. The dimensions included are physical functioning, social functioning, role physical, role emotional, mental health, vitality, bodily pain and general health. The enabled version is adapted to individuals with a mobility impairment. The questionnaire has a score range of 0 – 100, where a higher score represents a higher quality of life.

Usability. The usability of the app was tested with the System Usability Scale (SUS), a 10-item questionnaire assessing the usability of the product on a 10-point Likert scale ranging from 1 ("strongly disagree") to 10 ("strongly agree"). The sum of the results was rescaled to a total of 100, where a higher score represents a higher experienced usability [51].

Statistical Analysis

Shapiro-Wilk test, histograms and Q-Q plots were used to test for normality of the data. Demographics of the study population were described.

Data collected with the Fitbit were analysed with different models, depending on the distribution of the outcome variables. The physical activity outcome 'steps' was modelled with a random intercept mixed model. The data was not normally distributed and, therefore, square root transformed. Compound symmetry was used as repeated covariance type with a restricted maximum likelihood method for the mixed model. In this model, 'steps' was used as dependent variable with intervention period as independent variable. In case of sleep data, where data transformation could not achieve normal distribution, a random intercept panel linear model was performed, as this method does not require normal distributed data as an assumption [52]. In the two models the number of sleep minutes and sleep efficiency were the dependent variables with intervention period as independent variable.

Change in SoC was constructed as a dichotomous variable whether a changed occurred towards maintenance (=1) or not (=0). A change towards maintenance was considered when the SoC score increased with at least one step towards (5) "working to prevent relapse and consolidate gains (maintenance)". In case of a similar SoC score or a step downwards towards (1) "no intention to change", a score of 0 was assigned. For nutrition data, interaction effects between change in SoC and all nutrition outcomes were tested with a repeated measures ANOVA. Nutrition outcomes were set as dependent variables (pre and post) and the dichotomous variable for change in SoC as independent variables. For physical activity data, an interaction effect was included in the random intercept mixed model between change in SoC (dichotomous variable) and intervention period as independent variables and registered steps as dependent variable.

Pre and post-intervention changes on body composition, nutrition and the questionnaires SoC, PASIPD, body satisfaction, ESES, CIS20R, PSQI, SF-36[E] and SUS were tested with a paired-samples t-test or, when assumptions were violated, the non-parametrical alternative Wilcoxon signed-rank test.

Cohen's d effect sizes were calculated. In the situation of $n < 20$ the alternative Hedges' g was calculated. Effect sizes were interpreted as: $d < 0.2$ very small, $d = 0.2 – 0.5$ small, $d = 0.5 – 0.8$ medium, $d > 0.8$ large. When assumptions were violated, the effect size was determined by $z/(\sqrt{n})$ [53].

Significance was accepted at $p < .05$. In the case of multiple comparisons, a Bonferroni correction was applied by dividing .05 by the amount of tests performed for each aspect (SoC, nutrition, body composition and questionnaires). All data collected with the Fitbit were processed using R software (version 4.1.1, R Foundation for Statistical Computing, Vienna, Austria) within the Rstudio environment (Version 1.4.1717, Rstudio, Inc., Boston, MA, USA) [54,55]. Panel linear model analysis was performed with the plm package [55]. All other statistical analyses were performed with IBM SPSS Software (Version 27).

Results

Thirty-three participants were included in the study of which 30 completed the intervention period (figure 2). Of these 30 participants, three participants did not complete the nutrition diary on both pre and post-measurement, two did not complete the final questionnaires and one participant was unable to collect any data with the Fitbit due to technical issues throughout the intervention period. Demographic information of the 30 participants who finished the intervention period are presented in table 1. Due to the inability to measure body mass in a home setting when using a wheelchair, limited body mass and BMI data (n=19) are available.

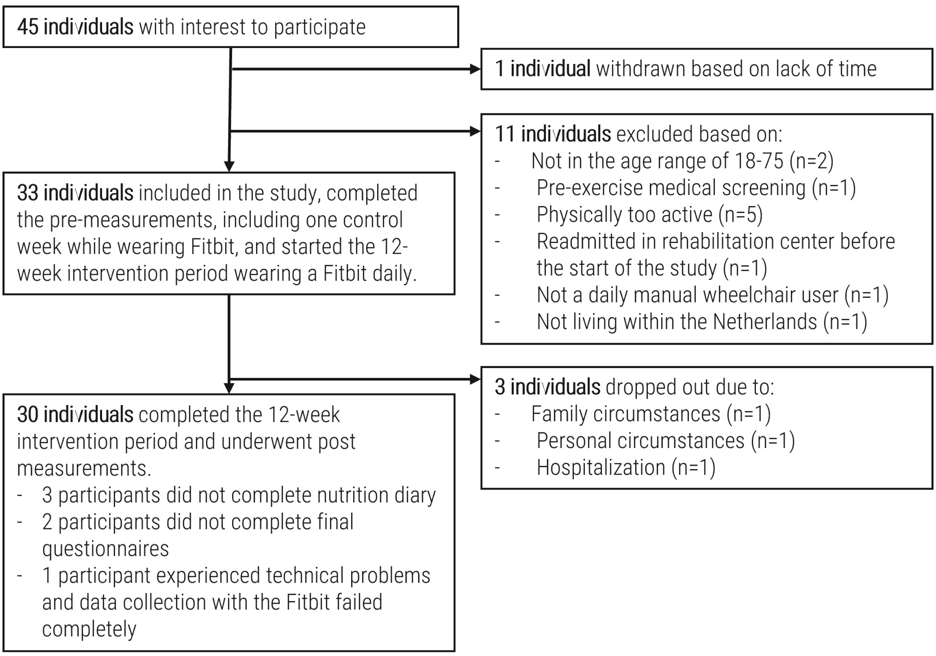


Figure 2. Flow chart of participant's inclusion.

Table 1. Demographic characteristics of the participants.

Characteristics	n	Frequency / Mean (SD)
Sex (female / male)	30	19 / 11
Age (y)	30	52.4 (11.1)
Height (m)	29	1.75 (0.10)
Body mass (kg)	20	79.9 (19.7)
BMI (kg/m^2)	20	25.8 (5.1)
Educational level	30	
Lower educational level		1
Middle educational level		10
Higher educational level		19
Characteristics chronic disability	30	
Spinal cord injury		20
Tetraplegia		6
Paraplegia		14
Unilateral lower-limb amputation		3
Cerebral palsy		1
Ehlers-Danlos syndrome		2
ADAM syndrome		1
Autoimmune cerebellar ataxias		1
Severe ankle trauma		1
Osteoarthritis of the spine		1

BMI = body mass index, ADAM = Amniotic deformity adhesion mutilation.

Table 2. Experienced stage of change on nutrition and physical activity pre and post intervention (n=28).

State of change regarding physical activity			
Stage of change pre intervention		**Stage of change post intervention**	
Stage of Change	**n**	**Stage of Change**	**n**
Precontemplation	1	Precontemplation	1
Contemplation	7	Contemplation	4
Preparation	14	Preparation	2
Action	0	Action	15
Maintenance	6	Maintenance	6
State of change regarding nutrition			
Stage of change pre intervention		**Stage of change post intervention**	
Stage of change	**n**	**Stage of change**	**n**
Precontemplation	0	Precontemplation	2
Contemplation	1	Contemplation	1
Preparation	6	Preparation	0
Action	1	Action	7
Maintenance	20	Maintenance	18

Stage of Change

Significance for change in SoC was accepted at a *p* value of .05 / 2 = .025. No significant change in SoC regarding physical activity (*p* = .034; effect size = .40) or nutrition (*p* = .81; effect size = .05) was found between pre to post-test. Sixteen participants shifted at least one stage regarding physical activity towards maintenance and six participants shifted at least one stage towards maintenance regarding nutrition. All frequencies are shown in table 2.

Fitbit Data

Physical Activity

A total of 2113 (80.1%) valid days were recorded out of 2639 available days, of which 332 (88.1%) valid week averages could be constructed for analysis out of 377 available weeks. This resulted in 112 (96.6%) valid period averages, calculated according to the requirements mentioned in the method section. The random intercept mixed model showed a tendency towards an increase in registered 'steps' over the intervention periods (*p* = .064). Results of the pairwise comparison of the control week with the intervention periods showed a significant increase in physical activity in the middle intervention period (+3.8 ± 1.5 √steps) (table 3), which represents an average daily increase of approximately 610 'steps' registered by the Fitbit. No significant change was found at the end of the intervention period on 'steps', with a small effect size (*d* = 0.13). No interaction effect was found (*p* ≥ .354) between change in SoC and physical activity during any intervention period when this was added as interaction to the mixed model.

5

Sleep Quality

A total of 2018 (76.5%) valid nights were recorded of the 2639 available nights, of which 319 (84.6%) valid week averages could be constructed of the 377 available weeks. This resulted in 108 (93.1%) valid period averages of the 116 available periods. The random intercept panel linear model showed a significant temporary reduced number of sleep minutes (-13.0 ± 6.1 min) and sleep efficiency (-1.5 ± 0.7%) registered by the Fitbit during the middle period, compared to the control week, as shown in table 3. At the end period of the intervention no significant changes were observed for number of sleep minutes or sleep efficiency with very small (*d* = -0.05) to small effect (*d* = -0.17) sizes respectively.

Table 3. Regression analyses on Fitbit data.

Random intercept mixed model	n	√steps β	Std. error	P value			
Control week	26	77.6	11.5				
Start period intervention	29	0.6	1.5	1.00			
Middle period intervention	28	3.8	1.5	**.042**			
End period intervention	29	1.5	1.5	.97			
		Sleep minutes			**Sleep efficiency (%)**		
Random intercept panel linear model	**n**	**β**	**Std. error**	**P value**	**β**	**Std. error**	**P value**
Control week	25	427.1	83.4		93.8	1.3	
Start period intervention	29	-7.7	6.0	.20	-1.0	0.7	.14
Middle period intervention	27	-13.0	6.1	**.035**	-1.5	0.7	**.032**
End period intervention	27	-9.7	6.1	.12	-1.2	0.7	.10

Control week was used as reference.
n = amount of period averages available for analysis of each period.
β = average variable outcome (control week) and average difference compared to control week.
Std. error = standard error.

Nutrition

Data of one participant were excluded from analysis due to unrealistic nutrition diary values (i.e., daily energy intakes were implausibly low). Significance was accepted at .05 / 7 = .007. A significant reduction (-1022 ± 434 kJ) in energy consumption was found post-intervention with a medium effect size. Additionally, the amount of consumed protein (-8.3 ± 5.0 g) and fat (-13.1 ± 5.0 g) was significantly lower post intervention with a medium effect size for protein and a large effect size for consumed fat (table 4). No interaction effect was found ($p \geq .257$) between change in SoC and intervention period for any of the nutrition outcomes.

Table 4. Nutritional intake pre and post 12-week intervention based on diet records (n=26).

Daily average consumed	Pre Mean (SD)	Post Mean (SD)	P value	Effect size d
Energy (kJ)	6789 (1743)	5767 (1364)	**.001**	.71
Protein (g)	70.2 (18.4)	61.9 (17.4)	**.005**	.61
Fat (g)	67.5 (18.0)	54.4 (17.7)	**<.001**	.87
Carbohydrates (g)	183.6 (70.9)	160.2 (51.1)	.071	.37
Protein (%)	17.6 (3.7)	18.1 (3.9)	.42	.16
Fat (%)	37.9 (8.5)	35.5 (8.2)	.11[a]	.32
Carbohydrates (%)	44.5 (8.9)	46.4 (8.9)	.26	.23

[a]Indicates non-parametric test used with corresponding effect size due to violation of normality.

Body Composition

Body composition data of 27 participants at pre and post-intervention were available, including body mass data of 19. Significance was accepted at .05 / 3 = .017. A significant reduction was found overtime in body mass (-2.7 ± 6.2 kg), BMI (-0.8 ± 1.5 kg/m2) and waist circumference (-3.3 ± 3.9 cm) with medium effect sizes for body mass and BMI and a large effect size for waist circumference (table 5).

Table 5. Body composition changes pre and post 12-week intervention (n=27).

Body composition	n	Pre Mean (SD)	Post Mean (SD)	P value	Effect size d
Body mass (kg)	19	80.9 (19.7)	78.7 (18.4)	**.015**	.61[a]
BMI (kg/m^2)	19	26.2 (4.9)	25.4 (4.4)	**.007**	.68[a]
Waist circumference (cm)	27	99.3 (15.1)	96.0 (13.8)	**<.001**	.80

[a]Hedges' g effect size.
BMI = Body mass index.

Questionnaires

Significance was accepted at a *p* value of .05 / 15 = .003. A significant increase (+7.8 ± 3.0 MET h/day) in physical activity was found according to the PASIPD questionnaire, with a medium effect size. A significant improvement was found in experienced body function (+1.22 ± 0.36), body appearance (+1.10 ± 0.43) and total body satisfaction (+1.19 ± 0.31), with medium effect sizes for body function and body appearance and a large effect size for overall body satisfaction. No significant change was found in exercise self-efficacy according to the ESES questionnaire. A significant reduction in experienced fatigue was registered with the CIS20R questionnaire (-15.1 ± 6.7) with a medium effect size. According to the PSQI questionnaire, no significant change was found in sleep quality during the intervention. Within the SF-36E questionnaire, significant improvements were found on the domains mental health (+7.3 ± 4.1) and vitality (+9.1 ± 5.0), all with a medium effect size. No significant changes were found on the domains physical functioning, social functioning, role limitation physical, role limitation emotional, pain and general health perception. The participants evaluated the usability of the WHEELS app with a mean SUS score of 72.5 ± 17.5 with a score range of 32.5 and 100. Outcomes of all the questionnaires can be found in table 6.

Table 6. Results from questionnaires pre and post 12-week intervention (n=28).

Questionnaire	Pre Mean (SD)	Post Mean (SD)	P value	Effect size d
PASIPD[a] (MET h/day)	11.1 (10.3)	18.9 (12.4)	**.001[a]**	.65
Body satisfaction	-.61 (1.12)	0.58 (1.21)	**<.001[a]**	.80
Body function	-.53 (1.31)	0.69 (1.40)	**<.001[a]**	.76
Body appearance	-.80 (1.46)	0.30 (1.75)	**<.001[a]**	.67
ESES[c]	33.2 (4.5)	34.8 (4.0)	.092[a]	.32
CIS20R[d]	74.2 (25.1)	59.1 (24.9)	**<.001**	.79
PSQI[e]	7.1 (3.3)	6.7 (2.3)	.71	.07
SF-36E[f]				
Physical functioning	41.8 (24.0)	49.8 (26.8)	.059	.37
Social functioning	71.4 (22.8)	73.2 (19.2)	.66[a]	.08
Role limitation physical	47.1 (23.8)	57.1 (22.4)	.012	.51
Role limitation emotional	78.9 (23.3)	81.3 (21.0)	.81[a]	.04
Mental health	72.5 (17.5)	79.8 (13.0)	**.002[a]**	.58
Vitality	54.7 (19.0)	63.8 (18.7)	**.002**	.64
Pain	39.4 (10.2)	62.1 (20.5)	.077	.35
General health perceptions	53.0 (20.7)	57.3 (20.2)	.11	.31

[a]Indicates non-parametrical test used with corresponding effect size due to violation of normality.
PASIPD = Physical Activity Scale for individuals with Physical Disability, ESES = Exercise Self-Efficacy Score, CIS20R = Checklist Individual Strength, PSQI = Pittsburgh Sleep Quality Index, SF36[E] = Short Form Health Survey 36 Enabled.

Discussion

Principal Findings

Findings of this study indicate that the WHEELS lifestyle app with an in-app coach and connected with an activity tracker partly supports a change towards a healthier lifestyle. No significant changes in SoC were found regarding physical activity and nutrition. No significant lasting changes in physical activity and sleep quality were observed based on Fitbit data. No interaction effect was found between SoC and outcomes on physical activity and nutrition. Participants showed a reduction in body mass, BMI and waist circumference, which seems largely caused by changes in diet, as a significant reduction was found in energy intake and amount of fat and protein post intervention. The questionnaire data showed that after the intervention the participants experienced an increase in body satisfaction, reduced fatigue and improved mental health and vitality.

Similar results on body composition changes were found during a previously conducted pilot study [12]. In the present study medium effect sizes were found on reduced body mass and BMI and a large effect size was found on reduced waist circumference, showing good potential of this lifestyle app. This study seems to confirm that the app supports weight loss in wheelchair users with an above average effect size (d = .61) on body mass compared to other mHealth weight loss programs (average d = .37) [57]. In total 74% of the participants lost weight and reduced their waist circumference. The validity of the body composition measurements is somewhat questionable, as they were all self-administered at home due to a global pandemic, instead of in a controlled environment by a trained researcher. However, diet records showed a reduced energy intake in 77% of the participants and a reduced intake of grams of fat and protein supporting both of our findings. Therefore, it seems plausible that the improvements in body composition reflect reality. Although the nutritional results are promising, there is still room for improvement on the macronutrient ratio intake of fat, as it shows a high relative intake with 35.5% of the total energy intake post intervention, where in general a range of 20-35% is recommended [58].

The contribution of physical activity on the body composition changes was limited, as only a temporary increase in physical activity was registered by the Fitbit during the middle period of the intervention. In the end period of the intervention, the increase in physical activity found was no longer significant compared to the control week. These results are in line with the previous conducted pilot study [12] and other studies [10]. Change in dietary behaviour is more likely to last than change in physical activity [10], which is also reflected by the SoC results found in this study considering the large number of participants who considered themselves in the maintenance stage in diet behaviour. Surprisingly, in the present study participants subjectively experienced an increase in their physical activity level based on the PASIPD questionnaire outcomes, in contrast to the objective Fitbit data. Possibly, participants experienced a greater increase in physical activity, because they were working on their lifestyle. However, discrepancies can exist between objectively measured and subjectively experienced behaviour. Previous research showed that non-ambulatory people tend to overestimate their physical activity level causing a low correlation in intensity (ρ = .24) and activity time (ρ = .22) between accelerometry and the PASIPD questionnaire [59], possibly explaining the discrepancies in results between the subjective and objective physical activity outcomes in this study.

The results on sleep quality, measured by the Fitbit, were unexpected, as a temporarily reduced registered sleep time and efficiency were found during the middle period of the intervention. The fact that during the same period a significant increase in physical activity was registered by the Fitbit, makes it even more surprising. Previous research showed small positive relationships between increased physical activity and improved sleep quality outcomes [60], with stronger relationships in individuals with present sleep problems [61]. This might apply to some of the participants in this study, as the average PSQI score pre intervention was 7.1 ± 3.3, which is above the cutoff point of 5, indicative of poor sleep quality [62]. One could wonder how meaningful the observed changes are, as only temporary reductions of 13 sleep minutes and 1.5% sleep efficiency were registered. A seasonal effect might have influenced sleep quality negatively, as previous research showed a reduced sleep time in the Spring season [63], which is when most of the study participants were included. There might be a ceiling effect on sleep efficiency making it difficult to improve sleep quality as the measured sleep efficiency in this study ranged between 54.5% and 98.8% with most participants already scoring above 90% in the control week, and thus, had little room for improvement [64]. However, Tobit analyses did not report censored observations in sleep efficiency, and, therefore, the data were analysed with panel linear regression. Another explanation for the limited change in sleep quality could be due to factors affecting sleep that could not be influenced by an mHealth application, such as spasms or (neurological) pain [65,66].

The WHEELS lifestyle app showed good results on health-related quality of life, body satisfaction and experienced fatigue. According to previous research, body satisfaction and physical and mental health are related [67]. Eating healthier is associated with improved body satisfaction, possibly partly explaining the improved body satisfaction in this study. The temporarily increased physical activity levels might also have influenced body satisfaction, mental health, fatigue and vitality, as they are all positively related to exercise [68,69]. More positive results were found in the present study with improved health-related quality of life, body satisfaction and reduced experienced fatigue, compared to the previous pilot study, which only showed an improved sleep quality according to the PSQI [12]. Participants experienced a better usability of the app in the present study with an average SUS score of 72.5 compared to 58.6 in the pilot study. The improved SUS score was most likely due to the improved in-app navigation function, a Fitbit integration allowing real time energy estimations and the availability of a lifestyle coach, possibly causing a larger intervention effect and a lower dropout rate.

Based on the willingness to participate in this study, it could be assumed that all participants were open to lifestyle change and, therefore, very unlikely in the “precontemplation” SoC. No significant shift was registered in SoC on physical activity, while participants did report a subjective increase in physical activity according to the PASIPD questionnaire. However, this did not result in an enduring increased physical activity level measured by accelerometry. No significant shift in SoC was registered for nutrition, although a significant change in diet was found during the intervention. It seems one single question regarding their readiness for change on lifestyle behaviour could not verify actual change, as no interaction was found between change in SoC and nutrition outcomes either. It might be that participants assumed their behaviour prior to the intervention was already healthy, but realised, based on feedback on their nutrition and physical activity received during the intervention, that this was not the case.

Strengths & Limitations

This study has several strengths. The study was conducted in an ecological setting in a manner how an mHealth application could be applied in practice. Physical activity and sleep behaviour were continuously measured with an accelerometer to measure possible changes over time objectively. However, this study also has limitations, the most obvious one being the lack of a control group. A randomised-controlled trial is a stronger design to confirm the promising results of this study. However, this would require a larger total sample size for similar statistical power [70], which is generally a challenge in population-specific research. Fitbit data used for physical activity were registered "steps" from the Fitbit, which is not specifically designed for wheelchair use. However, previous research has shown that the Fitbit is able to differentiate physical activity levels in wheelchair users [32], which is confirmed by the range of the registered daily steps (190 – 32,229) of the participants within this study. Overall, the accuracy of the heart rate registered by Fitbit during wheelchair activities seems decent, but can decline due to physiological changes, i.e., in people with tetraplegia [71]. Unfortunately, most outcome measures were self-reported due to a global pandemic. Body composition measurements were therefore limited and self-administered, resulting in a higher likelihood of measurement errors, which resulted in an intraclass coefficient correlation of .997 for both pre and post WC measurement. In addition, a strong correlation was found between the observed change in body mass and change in WC ($r = .809$, $p < .001$). However, clear instructions on how and when the measurements should be performed were given to all participants in order to limit errors. Although most participants (71%) stated that the global pandemic did not influence their lifestyle, it is plausible that the behaviour during this study might have been influenced due to the pandemic circumstances and results might, therefore, be less generalisable. No full lockdown took place during the study period, but small changes in governmental restrictions on society were applied during the study period, possibly influencing lifestyle behaviour of the participants on a small scale.

Conclusions

The WHEELS lifestyle app seems a valuable tool to support healthy lifestyle behaviour in wheelchair users. Although no enduring changes on objective physical activity and sleep were found, improved nutrition behaviour and body composition were registered combined with improved body satisfaction, mental health, vitality and reduced experienced fatigue. Thus, making the WHEELS lifestyle app a valuable and easy tool for wheelchair users to support healthy behaviour in a home setting.

Acknowledgements

This study was funded by Nederlandse Organisatie voor Wetenschappelijk Onderzoek, Regieorgaan SIA and the São Paulo Research Foundation under the big data and sports call 2016.

Declaration of Interest

The authors declare no conflict of interests.

References

1. World Health Organization. Global Health Risks: mortality and burden of disease attributable to selected major risks. Geneva; 2009.
2. World Health Organization. Public Spending on Health: A Closer Look at Global Trends. Geneva; 2018.
3. Ross SE, Flynn JI, Pate RR. What is really causing the obesity epidemic? A review of reviews in children and adults. J Sports Sci. 2016;34(12):1148–1153. [doi: 10.1080/02640414.2015.1093650]
4. Wu Y, Zhai L, Zhang D. Sleep duration and obesity among adults: A meta-analysis of prospective studies. Sleep Med [Internet]. 2014;15(12):1456–1462. [doi: 10.1016/j.sleep.2014.07.018]
5. Weil E, Wachterman M, Mccarthy EP, Davis RB, Day BO, Iezzoni LI, et al. Obesity Among Adults With Disabling Conditions. J Am Med Assoc. 2002;288(10):1265–1268.
6. World Health Organization. WHO fact sheet noncommunicable diseases. WHO fact sheet noncommunicable diseases. [cited 2021 Aug 12]. URL: https://www.who.int/news-room/fact-sheets/detail/noncommunicable-diseases
7. Sequi-dominguez I, Alvarez-bueno C, Martinez-vizcaino V. Effectiveness of Mobile Health Interventions Promoting Physical Activity and Lifestyle Interventions to Reduce Cardiovascular Risk Among Individuals With Metabolic Syndrome : Systematic Review Corresponding Author : J Med Internet Res. 2020;22(8).
8. Kitsiou S, Paré G, Gerber B, Jaana M. Effectiveness of mHealth interventions for patients with diabetes : An overview of systematic reviews. PLoS One. 2017;12(3).
9. Hutchesson MJ, Rollo ME, Krukowski R, Ells L, Harvey J, Morgan PJ, et al. eHealth interventions for the prevention and treatment of overweight and obesity in adults : a systematic review with meta-analysis. Obes Rev. 2015;16:376–392.
10. Fjeldsoe B, Neuhaus M, Winkler E, Eakin E. Systematic Review of Maintenance of Behavior Change Following Physical Activity and Dietary Interventions. Heal Psychol. 2011;30(1):99–109.
11. Bardus M, van Beurden SB, Smith JR, Abraham C. A review and content analysis of engagement, functionality, aesthetics, information quality, and change techniques in the most popular commercial apps for weight management. Int J Behav Nutr Phys Act. 2016;13(1). [doi:10.1186/s12966-016-0359-9]
12. Hoevenaars D, Holla JFM, Loo L, Koedijker JM. Mobile App (WHEELS) to Promote a Healthy Lifestyle in Wheelchair Users With Spinal Cord Injury or Lower Limb Amputation : Usability and Feasibility Study. JMIR Form Res. 2021;5(8). [doi:10.2196/24909]
13. Bartholomew LK, Markham CM, Ruiter RAC, Fernandez ME, Kok G, Parcel GS. Planning health promotion programs: an intervention mapping approach. 4th ed. San Fransisco, CA: Jossey-Bass; 2016.
14. Petty RE, Barden J, Wheeler SC. The elaboration likelihood model of persuasion: health promotions that yield sustained behavioral change. In: DiClemente RJ, Crosby RA, Kegler MC, editors. Emerging theories in health promotion practice and research: strategies for improving public health. 1st ed. San Fransisco, CA: Jossey-Bass; 2002. p. 71–99.
15. Prochaska JO, Redding CA, Evers KE. The transtheoretical model and stages of change. In: Glanz K, Rimer BK, Viswanath K, editors. Health behavior and health education: theory, research, and practice. 4th ed. San Fransisco, CA: Jossey-Bass; 2008. p. 98–120.
16. Brug J, van Assema P, Lechner L. Gezondheidsvoorlichting en gedragsverandering: een planmatige aanpak. 9e ed. Assen: Koninklijke van Gorcum BV.; 2017.

17. Champion VL, Skinner CS. The health belief model. In: Glanz K, Rimer BK, Viswanath K, editors. Health behavior and health education: Theory, research and practice. 4th ed. San Fransisco, CA: Jossey-Bass; 2008. p. 45–65.

18. Latham GP, Locke EA. New developments in and directions for goal-setting research. Eur Psychol. 2007;12(4):290–300.

19. McAlister AI, Perry CI, Parcel GS. How individuals, environments, and health behaviors interact: Social Cognitive Theory. In: Glanz K, Rimer BK, Viswanath K, editors. Health behavior and health education: theory, research, and practice. 4th ed. San Fransisco, CA: Jossey-Bass; 2008. p. 169–187.

20. Martin Ginis KA, van der Scheer JW, Latimer-Cheung AE, Barrow A, Bourne C, Carruthers P, et al. Evidence-based scientific exercise guidelines for adults with spinal cord injury: an update and a new guideline. Spinal Cord. 2017;1–14. [doi:10.1038/s41393-017-0017-3]

21. Bille K, Figueiras D, Schamasch P, Kappenberger L, Brenner JI, Meijboom FJ, et al. Sudden cardiac death in athletes : the Lausanne Recommendations. Eur J Cardiovasc Prev Rehabil. 2006;13(6):859–875.

22. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39:175–191.

23. Love R, Adams J, van Sluijs EMF, Foster C, Humphreys D. A cumulative meta-analysis of the effects of individual physical activity interventions targeting healthy adults. Obes Rev. 2018;19(8):1164–1172.

24. Rice IM, Rice LA, Motl RW. Promoting Physical Activity Through a Manual Wheelchair Propulsion Intervention in Persons with Multiple Sclerosis. Arch Phys Med Rehabil. 2015;96(10):1850–1858. [doi:10.1016/j.apmr.2015.06.011]

25. Dontje ML, Groot M De, Lengton RR, Schans CP Van Der, Krijnen WP. Measuring steps with the Fitbit activity tracker: An inter-device reliability study. Med Eng Technol. 2015;39(5):286–290.

26. Schofield WN. Predicting basal metabolic rate, new standards and review of previous work. Hum Nutr Clin Nutr. 1985;39:5–41.

27. Buchholz AC, McGillivray CF, Pencharz PB. Differences in resting metabolic rate between paraplegic and able-bodied subjects are explained by differences in body composition. Am J Clin Nutr. 2003;77(2):371–378.

28. Monroe MB, Tataranni PA, Pratley R, Manore MM, Skinner JS, Ravussin E. Lower daily energy expenditure as measured by a respiratory chamber in subjects with spinal cord injury compared with control subjects. Am J Clin Nutr. 1998;68:1223–1227.

29. Collins EG, Gater D, Kiratli J, Butler J, Hanson K, Langbein WE. Energy cost of physical activities in persons with spinal cord injury. Med Sci Sports Exerc. 2010;42(4):691–700.

30. Prochaska JO, Velicer WF. The Transtheoretical Change Model of Health Behavior. Am J Heal Promot. 1997;12(1):38–48.

31. The Netherlands Nutrition Centre. Gezond eten. [cited 2021 Oct 19]. Available from: https://www.voedingscentrum.nl/nl/gezond-eten-met-de-schijf-van-vijf.aspx

32. Maijers MC, Verschuren O, Stolwijk-Swüste JM, van Koppenhagen CF, de Groot S, Post MWM. Is Fitbit Charge 2 a feasible instrument to monitor daily physical activity and handbike training in persons with spinal cord injury? A pilot study. Spinal Cord Ser Cases. 2018;4(84). [doi:10.1038/s41394-018-0113-4]

33. Fitbit. What should I know about Fitbit sleep stages? [Internet]. [cited 2022 May 25]. Available from: https://help.fitbit.com/articles/en_US/Help_article/2163.htm#:~:text=Fitbit estimates your sleep stages,as rolling over%2Cetc.

34. Haghayegh S, Khoshnevis S, Smolensky MH, Diller KR, Castriotta RJ. Accuracy of Wristband Fitbit Models in Assessing Sleep: Systematic Review and Meta-Analysis. J Med Internet Res. 2019;21(11).

35. Skender S, Ose J, Chang-Claude J, Paskow M, Brühmann B, Siegel EM, et al. Accelerometry and physical activity questionnaires - a systematic review. BMC Public Health. 2016;16(1):515. [doi:10.1186/s12889-016-3172-0]

36. Trost SG, Mciver KL, Pate RR. Conducting accelerometer-based activity assessments in field-based research. Med Sci Sport Exerc. 2005;37(11):531–543.

37. Ortega RM, Perez-Rodrigo C, Lopez-Sobaler AM. Dietary assessment methods: dietary records. Nutr Hosp. 2015;31:38–45.

38. Osterkamp LK. Current perspective on assessment of human body proportions of relevance to amputees. Vol. 95, Journal of the American Dietetic Association. 1995. p. 215–218.

39. Himes J. New equation to estimate body mass index in amputees. J Am Diet Assoc. 1995;95(6):646.

40. Centraal Bureau voor de Statistiek. Standaard Onderwijsindeling 2021. 2021.

41. Washburn RA, Zhu W, McAuley E, Frogley M, Figoni SF. The physical activity scale for individuals with physical disabilities: Development and evaluation. Arch Phys Med Rehabil. 2002;83(2):193–200.

42. Reboussin BA, Rejeski WJ, Martin KA, Callahan K, Dunn AL, King AC, et al. Correlates of satisfaction with body function and body appearance in middle- and older aged adults: The activity counseling trial (ACT). Psychol Health. 2000 Mar 1;15(2):239–254. [doi:10.1080/08870440008400304]

43. Nooijen CFJ, Post MWM, Spijkerman DCM, Bergen MP, Stam HJ, Van Den Berg-Emons RJG. Exercise self-efficacy in persons with spinal cord injury: Psychometric properties of the Dutch translation of the exercise self-efficacy scale. J Rehabil Med. 2013;45(4):347–350.

44. McAuley E. Self-efficacy and the maintenance of exercise participation in older adults. J Behav Med. 1993;16:103–113.

45. Makowiec-Dabrowska T, Koszada-Wlodarczyk W. The CIS20R Questionnaire and its suitability for prolonged fatigue studies. Med Pr. 2006;57(4):335–345.

46. Vercoulen JHMM, Swanink CMA, Fennis JFM, Galama JMD, van der Meer JWM, Bleijenberg G. Dimensional assessment of chronic fatigue syndrome. J Psychosom Res. 1994;38(5):383–392.

47. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. Buysse DJ, Reynolds CF, Monk TH, Berman SR, Kupfer DJ. The Pittsburgh Sleep Quality Index: a new instrument for psychiatric practice and research. Psychiatry Res. 1989;28:193–213.

48. Mollayeva T, Thurairajah P, Burton K, Mollayeva S, Shapiro CM, Colantonio A. The Pittsburgh sleep quality index as a screening tool for sleep dysfunction in clinical and non-clinical samples: A systematic review and meta-analysis. Sleep Med Rev. 2016;25:52–73. [doi:10.1016/j.smrv.2015.01.009]

49. Froehlich-Grobe K, Andresen EM, Caburnay C, White GW. Measuring health-related quality of life for persons with mobility impairments: An enabled version of the short-form 36 (SF-36E). Qual Life Res. 2008;17(5):751–770.

50. Aaronson NK, Muller M, Cohen PDA, Essink-Bot ML, Fekkes M, Sanderman R, et al. Translation, validation, and norming of the Dutch language version of the SF-36 Health Survey in community and chronic disease populations. J Clin Epidemiol. 1998;51(11):1055–1068.

51. Brooke J. SUS: a "quick and dirty" usability scale. In: Jordan PW, Thomas B, Weerdmeester BA, McClelland AL, editors. Usability Evaluation in Industry. London: CRC Press; 1996.

52. William H. G. Econometric analysis. 6th ed. Upper saddle river: Prentice Hall; 2008. 11–19 p.

53. Tomczak M, Tomczak E. The need to report effect size estimates revisited. An overview of some recommended measures of effect size. Trends Sport Sci. 2014;1(21):19–25.

54. R Foundation for Statistical Computing. R software. Vienna, Austria;

55. Rstudio Team. RStudio: Integrated Development Environment for R. Boston, MA, USA: Rstudio, PBC; 2021. Available from: http://www.rstudio.com/.

56. Croissant Y, Millo G. Panel Data Econometrics in R : The plm Package. J Stat Softw. 2008;27(2).

57. Cavero-Redondo I, Martinez-vizcaino V, Fernandez-Rodriguez R, Saz-Lara A, Pascual-Morena C, Alvarez-bueno C. Effect of Behavioral Weight Management Interventions Using Lifestyle mHealth Self-Monitoring on Weight Loss: A Systematic Review and Meta-Analysis. Nutrients. 2020;12(7).

58. Manore MM. Exercise and the Institute of Medicine Recommendations for Nutrition. Curr Sports Med Rep. 2005;4(4):193–198.

59. Van Den Berg-Emons RJ, L'Ortye AA, Buffart LM, Nieuwenhuijsen C, Nooijen CF, Bergen MP, et al. Validation of the physical activity scale for individuals with physical disabilities. Arch Phys Med Rehabil. 2011;92(6):923–928. [doi:10.1016/j.apmr.2010.12.006]

60. Kredlow MA, Capozzoli MC, Hearon BA, Calkins AW, Otto MW. The effects of physical activity on sleep: a meta-analytic review. J Behav Med. 2015;38:427–449. [doi:10.1007/s10865-015-9617-6]

61. Montgomery P, Dennis JA. Physical exercise for sleep problems in adults aged 60+. Chochrane Database Syst Rev. 2002;(4).

62. Backhaus J, Junghanns K, Broocks A, Riemann D, Hohagen F. Test-retest reliability and validity of the Pittsburgh Sleep Quality Index in primary insomnia. J Psychosom Res. 2002;3:737–740.

63. Mattingly SM, Grover T, Martinez GJ, Aledavood T, Robles-Granda P, Nies K, et al. The effects of seasons and weather on sleep patterns measured through longitudinal multimodal sensing. npj Digit Med. 2021;4(76). [doi:10.1038/s41746-021-00435-2]

64. Youngstedt SD. Ceiling and floor effects in sleep research. Sleep Med Rev. 2003;7(4).

65. Biering-Sorensen F, Biering-Sorensen M. Sleep disturbances in the spinal cord injured: an epidemiological questionnaire investigation, including a normal population. Spinal Cord. 2001;39:505–513.

66. de la Vega R, Miró J, Esteve R, Ramírez-maestre C, López-Martinez AE, Jensen MP. Sleep disturbance in individuals with physical disabilities and chronic pain: The role of physical, emotional and cognitive factors. Disabil Health J. 2019;12:588–593.

67. Gillen MM. Associations between positive body image and indicators of men ' s and women ' s mental and physical health. Body Image. 2015;13:67–74. [doi:10.1016/j.bodyim.2015.01.002]

68. Hausenblas HA, Fallon EA. Exercise and body image : A meta-analysis. Psychol Health. 2006;21(1):33–47.

69. Mikkelsen K, Stojanovska L, Polenakovic M, Bosevski M. Exercise and mental health. Maturitas. 2017;106:48–56. [doi:10.1016/j.maturitas.2017.09.003]

70. Wang X, Kattan MW. Cohort Studies: Design, Analysis, and Reporting. Chest. 2020 Jul;158(1S):S72–78

71. Hoevenaars D, Yocarini IE, Paraschiakos S, Holla JFM, de Groot S, Kraaij W, et al. Accuracy of Heart Rate Measurement by the Fitbit Charge 2 During Wheelchair Activities in People With Spinal Cord Injury: Instrument Validation Study. JMIR Rehabil Assist Technol. 2022;9(1).

Chapter 6

General discussion

Summary of the main findings

The main research question was: can wheelchair users improve their lifestyle and health using a combination of standard wearable sensors and a customised mHealth platform? By gaining insight in the lifestyle of wheelchair users, provide an evidence-based mHealth application, combined with wearable technology, and evaluate lifestyle changes during a 12-week intervention in wheelchair users with a chronic lower-limb disability, we strived to answer the main research question.

The findings in **chapter 2** once more emphasize the necessity of health promotion for people with spinal cord injury (SCI). Results showed that it is difficult to combine both aerobic and strength exercises on a weekly basis for people with SCI, despite their well-known benefits on physical fitness and health. As expected based on previous research [1], an older age, being female, having a tetraplegia and a low educational level were negatively associated with exercise behavior. On a positive side, relatively low exercise levels were associated with improved respiratory function. Increased aerobic exercise levels were associated with improved physical fitness (VO2peak), exercise capacity (POpeak) and body composition. With no associations found between exercise levels and lipid profile or blood pressure, only limited results on health were found. This is probably attributed to their complex regulation and involvement of additional factors on top of exercise behavior. The evidence-based exercise guidelines for people with SCI seem to partly achieve what they are designed for and should, therefore, be used as a guide towards healthier physical activity behavior and health promotion.

Wearable technology could play a role in healthy lifestyle promotion with increasing value in the future considering the rapid technological developments. This also applies to wheelchair users, provided that this technology can accurately measure their physical activity behavior. **Chapter 3** shows that the heart rate recording accuracy of wearables, measured with the photoplethysmography (PPG) technique, could be less precise in people with SCI. Results showed that the heart rate recording accuracy is in general lower in people with an SCI than in able-bodied individuals, and fell just outside the acceptable mean absolute percentage error (MAPE) of ± 10% [2]. Accuracy severely dropped in people with lesion levels above Thoracic 1 during wheelchair activities (MAPE=20.43%) and strength exercise (MAPE= 22.29%). Therefore, PPG-based heart rate measurements should be taken with caution in people with high lesion SCI, especially when the importance of accurate data is high. Solutions are ought to be found for this population to avoid exclusion of future wearable developments.

In **chapter 4,** the developmental process and experienced usability and feasibility of the WHEELS mHealth application is presented. The development process describes how intervention goals were determined with the corresponding behavior change techniques and implemented in the WHEELS app. The results of the pilot study showed a reasonable usability score with suggestions for improvement. The application seemed feasible to deploy on a larger scale and the first results on lifestyle change were promising.

Eventually, integration of a wearable was included in the WHEELS app and was evaluated on a larger scale of which the results are presented in **chapter 5**. During a 12-week intervention study, lifestyle-related outcomes on physical activity, diet and sleep were collected together with self-reported body composition measurements and health-related quality of life. Significant positive changes were found on diet, body composition, experienced body satisfaction, fatigue, mental health and vitality. No enduring changes were found on physical activity and sleep behavior. Based on these results, the app seems like an easy and feasible tool for wheelchair users with a chronic disability to support a healthy lifestyle in a home setting, particularly for dietary behavior.

With this, the main research question has also been answered. Based on the results we can conclude that a combination of a standard wearable sensor combined with a customized mHealth platform can improve the lifestyle of wheelchair users. However, room for improvement remains with no enduring improvements observed in physical activity and sleep quality. Aspects of wearables and mHealth that could contribute to a better intervention effect are further discussed below and further development and future research is suggested.

Promoting physical activity in wheelchair users

Science has proven the benefits of regular physical activity on health such as reduced risk for all-cause mortality, prevention of many chronic diseases, improved mental health, quality of life and cognitive function [3–8]. To translate this knowledge to society and provide information and guidance regarding the dose-response relationship of physical activity and health benefits, multiple guidelines have been developed over time for people with disabilities [9]. This includes guidelines for people with SCI, with those of Martin Ginis et al. (2017) and Tweedy et al. (2017) being the most recent guidelines [10,11]. Although more emphasize was put on population specific evidence-based knowledge, the strength of the used evidence varied. Moderate to high confidence ratings were found regarding fitness and cardiometabolic health for people with chronic SCI [12]. However, the available evidence seemed inadequate to obtain dose-response relationships between exercise and fitness and cardiometabolic health, primarily due to limited available population-specific scientific literature [10,13,14]. The results in chapter 2 support that the developed guidelines achieve what they were designed for and that increased physical activity is associated with increased physical fitness and health.

Group allocation in chapter 2 was based on the outcomes of questions about the amount of time spent on planned and structured aerobic exercise extracted from the Physical Activity Scale for Individuals with Physical Disabilities (PASIPD) questionnaire. In both SCI exercise guidelines [10,11] exercise is defined as "planned, structured, and repetitive physical activity that is performed to maintain or improve fitness [15]". This excludes unstructured and unplanned physical activities like manual wheelchair propulsion during daily life, or planned daily activities which are not considered as a sport or recreational activity, e.g., household chores. However, moderate (MET>3) to vigorous (MET>6) intensities [16] are the intensities required to achieve these guidelines and its corresponding health benefits and are often also achieved during activities of daily living [17]. This could have caused an underestimation of the people possibly reaching the thresholds of the SCI physical activity guidelines on both the aerobic and strength exercise aspect. Additionally, the effect of strength exercise was not taken into account during the multiple regression analyses in chapter 2, possibly influencing the results, as strength exercise is also associated with health benefits [18]. Putting more emphasize on increasing unstructured and unplanned physical activity on a daily bases could contribute to an increased accumulated physical activity time spent within moderate to vigorous intensities, as this seems like an overlooked opportunity as suggested by Cowan et al. 2022 [19]. An opportunity to quantify the accumulation of unplanned physical activity together with planned exercise activity to achieve the desired physical activity levels could be the application of wearable technology.

Another often overlooked aspect associated with health outcomes is sedentary behavior. There is growing evidence showing that longer accumulated bouts of sedentary behavior is a greater threat to health than a similar total time of sedentary behavior that is periodically discontinued [20,21]. Considering the recent developed guidelines included specifically sedentary behavior [22,23], it shows that the interest and relevance of this topic is growing. Based on literature it is clear that sedentary behavior is related to health and people should avoid prolonged sedentary bouts [24]. Short term benefits were found on the glucose level in people with paraplegia when prolonged sedentary bouts were avoided, reducing risks in cardiovascular disease [25]. Although no clear evidence regarding the dose-response relationship seems available for either able-bodied or individuals with a disability [22,23], it is clear that prolonged sedentary behavior should be avoided. Gaining insight on the dose-response relationship between sedentary behavior and health could benefit future physical activity recommendations, especially for wheelchair users. Considering the additional barriers for physical activity, ensuring the best dose-response relationship on sedentary behavior could achieve the best health benefits with relative low physical activity levels in wheelchair users, in which unstructured physical activity could play a role.

Additionally, a shift in the approach to promote physical activity could benefit how the population responds to the received information and enlarge the effect of the message on health promotion. A relatively low amount of exercise activity was associated with improved physical fitness, supporting the claim that most improvements occur when individuals transition from inactive to active [26]. Previous research showed that even with small changes in physical activity, significant improvements in health could be achieved going from inactive to a little more active [27]. Considering that an estimated 36.9% individuals with SCI in the Netherlands did not meet the least strenuous aerobic exercise guidelines in chapter 2, and can be considered inactive, a relative small change in behavior could achieve significant fitness and health benefits for a large group. This could also support that fitness and health benefits could be achieved outside structured exercise in short bouts during daily life. Knowing that increased activity is curvilinear related to increased health benefits, one could argue to suggest the recommendation to "simply become more active", with exemption from the persons who are already extremely active [5,28]. Meeting exercise guidelines should be a goal to achieve, however, it could be promoted differently to avoid unattainable goals. In a worst-case scenario, shifting from meeting the MG fitness guidelines towards meeting the MG cardiometabolic or Tweedy exercise guidelines could translates into a 225% and 375% increase in exercise time, respectively. Generic promotion without threshold or smaller relative steps that are more realistic (e.g., increase 10%) could facilitate physical activity promotion towards meeting the exercise guidelines. Removing recommended activity thresholds could positively affect the results of a message in health promotion [29].

Wearable use in wheelchair users

Wearables and activity trackers can support users in the registration inside and outside planned and structured physical activity with the goal to reach healthy physical activity levels. Some of the most commonly present behavior change techniques in activity trackers are self-monitoring, feedback, goal-setting, social support, social comparison, cues and rewards [30]. If these functionalities are well integrated into mHealth and are used optimally, the behavior change effects can be significantly larger [31]. However, activity trackers often show low adoption rates for wheelchair use and usually report their primary metric on physical activity in "steps" [32]. Although this feature is able to detect differences in activity levels in wheelchair users between days [33], it is not inclusive for wheelchair users and provides inaccurate feedback. Recent commercially available wearables, such as the Apple Watch, have an integrated wheelchair setting which replaces step count with stroke counts, but still show variable accuracy which is task and push frequency dependent [34]. In addition, the user interface is often not designed and therefore not usable for individuals with, e.g., limited hand function. Despite these cons, there are some benefits in using commercial activity trackers, that contribute to a high wear compliance. The combination of convenience, proximity and provided real-time feedback is directly related to the individual's satisfaction [35]. Combined with a well-designed user interface, this positively influences wear compliance and, therefore, exposure to behavior change techniques, possibly explaining the high wear compliance in chapter 5.

A solution for the low accuracy rates of commercial wearables for wheelchair use [34,36] would be better wheelchair and population specific algorithms which fit their corresponding activities. Literature is available on suggested wearable positioning [37], wheelchair activity recognition [38], accelerometry-based intensity level cut-off points [39,40], and energy expenditure estimation during wheelchair activities [41–43]. However, even energy expenditure models specifically designed for wheelchair users with SCI showed varied performance and often scored poorly [44]. In addition, the accuracy of energy expenditure estimation in able-bodied individuals with commercially available activity trackers also show varied results [45], confirming the complexity to develop accurate energy estimation models. Although wheelchair-specific estimation models might provide more suitable feedback than prediction models available in commercial activity trackers, the wheelchair-specific models are usually designed based on and for research-graded accelerometers. These are usually not combined with a sophisticated user interface and do not provide similar convenience and feedback, and therefore, lower satisfaction than commercially available wearables [35]. Less persuasive technologies are integrated in the research-graded wearable and user interface, restricting their role and potential in lifestyle and health promotion. Commercially available wearables are more affordable [46], comfortable to wear and user friendly [47]. However, available wheelchair-specific estimation models are impossible to implement in commercially available wearables due to copyright and their nondisclosed algorithms, making it challenging to provide wheelchair users a similar user experience as able-bodied individuals with commercial wearables. Vice versa it is too expensive to design and develop a whole new user interface and application that provides similar experience and features such as the Fitbit or Apple Watch for a relatively small population. Ideally, the trend to include wheelchair functions, like in the Apple Watch, will be adopted by the majority of the commercial brands in the near future and adjust their algorithms and models based on the available data and literature for wheelchair users.

However, including commercial wearables to monitor behavior within research also includes a different kind of challenge. With the increasing demands on data safety and privacy requirements during research, privacy regulations are directly related to wearable choice and adoption in research [48]. The implementation of the General Data Protection Regulation (GDPR), new data safety requirements became effective in 2018 and is considered as “the toughest privacy and security law in the world” [49]. Research-graded activity monitors such as Actigraph and Active8 allow offline collection, which is often not possible in commercially available wearables such as Fitbit and Apple. With their data server located in the United States and automatically uploading data when synchronizing, using Fitbit or Apple in a research setting within the European Union becomes very challenging, as research data is not allowed to leave the EU, unless a data processing agreement between parties has been organized. To allow optimal usage of these wearables in future research settings, possibly in combination with mHealth, involved parties are ought to find a solution for this issue without endangering the data security. This could benefit the accessibility, affordability and quality of future wearables and mHealth combinations in research and eventually publicly available products.

mHealth

mHealth is becoming a popular mode within healthcare and health promotion due to its cost-effective design and broad accessibility [50]. However, with over 300,000 mHealth apps available which continues to grow, the quality of the content can vary significantly [51,52]. Literature shows most of these available apps are not evidence based or are conflicting with public health guidelines and lack theoretical foundation [52–54], user or expert involvement [52,53,55], evidence of effectiveness [52,53,55] and privacy security assurance [52,53,55]. These issues were all tackled during the development process of the WHEELS app by including experts, potential users and the app developer and by adopting theory and evidence-based content and behavior change techniques [56]. Results of chapter 4 and 5 show that mHealth is an easy and feasible tool to provide feedback and improve awareness of someone’s diet, eventually supporting behavior change and improve health-related quality of life in wheelchair users with a chronic lower-limb disability.

Results from both chapters 4 and 5 show that the persuasive behavior change techniques present in the WHEELS app elicit diet changes. The combination of several behavioral change techniques such as feedback, goal setting and providing information induce awareness, directly influencing daily dietary choices. Despite the fact that the overall results seem promising, room for improvements remain. The reduction of total energy and fat intake was accompanied with a reduction in total protein intake, which may be undesirable. Protein is an important aspect of a healthy diet, and even more so in wheelchair users with, for example, SCI or lower limb amputation [57]. Energy needs differ based on lesion or amputation level and should be taken into account when estimating energy expenditure [58,59], which was not included in the WHEELS app. Therefore, better population-specific and individualized diet recommendations could be implemented based on personal and disability-related characteristics. This could improve the accuracy of the received feedback and recommendations on the energy intake and proportions of macronutrients and thus dietary choices.

Only limited positive results were found in the other lifestyle outcomes. No lasting changes were reported on physical activity and sleep quality. The intervention showed a small effect size (d = 0.13) on physical activity in chapter 5, which is similar compared to previous literature on mHealth interventions focusing on physical activity [60,61]. Physical activity appears to be a more challenging behavior to change compared to diet [62]. However, a recent systematic review showed moderate effect sizes with significant improvements in physical activity, showing the potential of mHealth on physical activity promotion [63]. Surprisingly, effect sizes up to twice as high were found in the sick and at-risk populations compared to healthy populations. A probable cause for this finding would be a lower baseline activity level, explaining a relatively larger increase in physical activity level. The participants included in the studies in chapter 4 and 5 could be considered at-risk populations (inactive, sedentary or overweight populations) with low baseline activity levels, however, only small effect sizes were found on physical activity. A possible explanation for the lower effect size compared to other recent mHealth interventions could be the additional physical, personal, social and environmental barriers wheelchair users experience [64–66]. These are difficult or impossible to tackle through mHealth, compared to possible other at-risk populations from the systematic review, reducing the intervention effect.

In addition, a small (non-significant) reduction in sleep quality was registered by the Fitbit. However, one could question how meaningful these changes were, as only an average of -9.7 sleep minutes and -1.2% sleep efficiency was registered at the end of the intervention period. Sleep quality is more challenging to influence, as altered sleep behavior is not a guaranteed increased sleep quality. In physical activity and diet, behavior change directly translates into a healthier lifestyle. A possible reason why intervention effects on sleep quality were limited was due to the poor integration of sleep information of the Fitbit into the WHEELS app. The registered sleep time and sleep efficiency was not presented within the WHEELS app, meaning that participants had to extract information on their sleep behavior separately from the Fitbit app. As a result, less persuasive behavior change techniques were applied on the aspect of sleep. Information was, therefore, most likely the most dominant behavior change technique, possibly leading to poorer intervention effects and usability. Integrating feedback received on sleep behavior from the Fitbit into the WHEELS app could possibly strengthen and improve the intervention effect on sleep behavior and eventually sleep quality.

Another explanation for the limited positive intervention results could have been the lack of personal guidance. The pilot study described in chapter 4 was performed with both a stand-alone and remotely-guided group receiving support from Functional Exercise Therapy students. Despite the fact that participants who received remote-guidance reported limited effect of the phone consultations in their exit interview, possibly due to their little experience with lifestyle coaching of the students, results at the end of the pilot study were yet in favor of the remotely-guided group. Additionally, the stand-alone group reported that a consultant could have benefitted them both in user experience and behavior change. However, the sample size was small and difficult to generalize. During the intervention study described in chapter 5, all participants had access to in-app support from a professional lifestyle coach, who was consulted regularly for lifestyle-related support and app functionalities throughout the intervention. However, human in-app guidance was only provided on the initiative of the participants. Better results were found on behavior change in physical activity in designs that would combine mHealth with in-person interactions [67,68], which could suggest the intervention effect could be improved with in-person blended guidance. However, in a recent systematic review, no differences were found between stand-alone and a blended or remotely-guided version, showing varying evidence regarding blended interventions [63]. With the constant developments in technology, more advanced stand-alone interventions could be produced in the future with better personal-tailored automated coaching and goal setting, further increasing intervention effects. This could potentially work if all earlier described challenges are solved, i.e., providing a suitable wearable for wheelchair users, incorporated with mHealth software that allows for more sophisticated algorithms and data processing with personalized feedback to optimize the potential and combination of all health promoting techniques. Until then, blended or remote-guided seems to benefit mHealth users possibly influencing the effectiveness. However, the involved healthcare professionals should possess the competencies to be able to optimize utilization of mHealth in the support of behavior change.

Clinical implications

Based on the results of this thesis there are several potential clinical implications. Physical activity is highly associated with fitness benefits. Small increases in exercise time are associated with significant improvements in physical fitness in inactive people with SCI. Therefore, any increase in physical activity in inactive wheelchair users is valuable and worth the effort. A possibly overlooked opportunity to achieve this, is unstructured physical activity [19].

Wearable use could support and motivate behavior change in physical activity. Although commercial wearables, such as the Fitbit Charge 2 and 3, used in chapter 3 and 5, are not specifically designed for wheelchair use, they can still be valuable for health promotion.

Increased physical activity behavior is reflected by the feedback given by the Fitbit and could therefore be still valuable in monitoring physical activity. However, when the importance of accurate data is high, i.e., in some clinical settings, caution is recommended, and especially in people with high SCI lesions, the use of PPG-based heart rate data should be avoided.

mHealth is a valuable, cost-effective tool to support healthy behavior. Although many challenges occur during the development of an evidence-based mHealth app with accurate feedback based on wearable data, results show wheelchair users can benefit and improve their lifestyle from population-specific mHealth interventions. With relatively little guidance, mHealth can be implemented as a tool to support lifestyle change in a cost-effective way.

Future research

To maximize intervention effects, a better understanding is needed of the dose-response relationship of physical activity and sedentary behavior in wheelchair users with a chronic disability. Gaining better insights in the dose-response relationships on both of these aspects could allow for increased physical fitness and health intervention results. Additional options could arise on more specific physical activity promotion with inclusion of smaller or no thresholds, to avoid unattainable goals, possibly increasing the effect of the message.

Chapter 3, i.e. the Fitbit validation study, shows the importance of including different populations in development and validation studies. In order to include all populations in future developments and wearable opportunities, alternative algorithms are needed to allow accurate PPG-based heart rate data for people with high SCI lesions. Ideally, these algorithms are applicable on a broad range of wearables, so future developments of mHealth apps are not limited one specific wearable that is considered accurate for a specific population. In future research it is therefore of importance to keep conducting population-specific development and validation studies on new technologies and wearables.

With the rapid development of (wearable) technology, mHealth interventions are only at the beginning of their potential. With suitable wearables for wheelchair use that report accurate feedback on activity, intensity and energy expenditure with high user friendliness, could benefit the wheelchair community. In combination with an mHealth intervention which includes personalized automated feedback and goalsetting with evidence-based content could strengthen the intervention effect on lifestyle-related behaviors and eventually health and wellbeing. mHealth programs should be further developed to achieve the combination of the aforementioned features specified for wheelchair users.

References

1. Rauch A, Hinrichs T, Oberhauser C, Cieza A. Do people with spinal cord injury meet the WHO recommendations on physical activity? Int J Public Health. 2016;61(1):17–27.

2. The Association for Advancement of Medical Instrumentation. Cardiac monitors, heart rate meters, and alarms. Arlington; 2002.

3. World Health Organization. Global Health Risks: mortality and burden of disease attributable to selected major risks. Geneva; 2009.

4. Bull FC, Al-Ansari SS, Biddle S, Borodulin K, Buman MP, Cardon G, et al. World Health Organization 2020 guidelines on physical activity and sedentary behaviour. Br J Sports Med. 2020;54(24):1451–1462.

5. Warburton DER, Bredin SSD. Health benefits of physical activity: a systematic review of current systematic reviews. Curr Opin Cardiol. 2017;32(5):541–556.

6. Sofi F, Valecchi D, Bacci D, Abbate R, Gensini GF, Casini A, et al. Physical activity and risk of cognitive decline: a meta-analysis of prospective studies. J Intern Med. 2010;269(1):107–117.

7. World Health Organization. Obesity and Overweight. 2021 [cited 2022 Feb 23]. Available from: https://www.who.int/news-room/fact-sheets/detail/obesity-and-overweight

8. World Health Organization. Global recommendations on physical activity for health. Geneva; 2010.

9. Latimer-cheung AE, Martin Ginis K, Hicks AL, Motl RW, Pilutti LA, Duggan M, et al. Development of Evidence-Informed Physical Activity Guidelines for Adults With Multiple Sclerosis. Arch Phys Med Rehabil. 2013;94(9):1829–36. [doi:10.1016/j.apmr.2013.05.015]

10. Martin Ginis KA, van der Scheer JW, Latimer-Cheung AE, Barrow A, Bourne C, Carruthers P, et al. Evidence-based scientific exercise guidelines for adults with spinal cord injury: an update and a new guideline. Spinal Cord. 2017. [doi:10.1038/s41393-017-0017-3]

11. Tweedy SM, Beckman EM, Geraghty TJ, Theisen D, Perret C, Harvey LA, et al. Exercise and Sports Science Australia (ESSA) Position Statement on exercise and spinal cord injury. J Sci Med Sport [Internet]. 2017;20(5):422–3. [doi:10.1016/j.jsams.2016.02.001]

12. Balshem H, Helfand M, Schünemann HJ, Oxman AD, Kunz R, Brozek J, et al. GRADE guidelines: 3. Rating the quality of evidence. J Clin Epidemiol. 2011;64(4):401–406.

13. Ginis KAM, Latimer-cheung AE, West CR. Commentary on “The First Global Physical Activity and Sedentary Behavior Guidelines for People Living With Disability.” J Phys Act Heal. 2021;18:348–349.

14. van der Scheer JW, Martin Ginis KA, Ditor DS, Goosey-tolfrey V, Hicks AL, West CR, et al. Effects of exercise on fitness and health of adults with spinal cord injury: a systematic review. Neurology. 2017;89(7):736–745.

15. Caspersen CJ, Powell KE, Christenson GM. Physical activity, exercise, and physical fitness: definitions and distinctions for health-related research. Public Health Rep. 1985;100(2):126–131.

16. American College of Sports Medicine. ACSM’s guidelines for exercise testing and prescription. 9th ed. Philadelphia: Lippincott Williams & Wilkins; 2013.

17. Collins EG, Gater D, Kiratli J, Butler J, Hanson K, Langbein WE. Energy cost of physical activities in persons with spinal cord injury. Med Sci Sports Exerc. 2010;42(4):691–700.

18. Stamatakis E, Lee I, Bennie J, Freeston J, Hamer M, O'Donovan G, et al. Does Strength-Promoting Exercise Confer Unique Health Benefits? A Pooled Analysis of Data on 11 Population Cohorts With All-Cause, Cancer, and Cardiovascular Mortality Endpoints. Am J Epidemiol. 2017;187(5):1102–1112.

19. Cowan RE, Silveira SL, Helle T, Læssøe U, Rosenbeck K, Bangshaag J, et al. Lifestyle physical activity in manual wheelchair users - an overlooked public health opportunity. Spinal Cord. 2022;60:190–192.

20. Saunders TJ, Larouche R, Colley RC, Tremblay MS. Acute Sedentary Behaviour and Markers of Cardiometabolic Risk: A Systematic Review of Intervention Studies. Fernandez ML, editor. J Nutr Metab. 2012;2012:712435. [doi:10.1155/2012/712435]

21. Farrahi V, Kangas M, Kiviniemi A, Puukka K, Korpelainen R, Jämsä T. Accumulation patterns of sedentary time and breaks and their association with cardiometabolic health markers in adults. Scand J Med Sci Sports. 2021;31(7):1489–1507.

22. Dempsey PC, Biddle SJH, Buman MP, Chastin S, Ekelund U, Friedenreich CM, et al. New global guidelines on sedentary behaviour and health for adults: broadening the behavioural targets. Int J Behav Nutr Phys Act. 2020;17(1).

23. Carty C, van der Ploeg HP, Biddle SJH, Bull F, Willumsen J, Lee L, et al. The First Global Physical Activity and Sedentary Behavior Guidelines for People With Disability. J Phys Act Heal. 2021;18:86–93.

24. Saunders TJ, McIsaac T, Douillette K, Gaulton N, Hunter S, Rhodes RE, et al. Sedentary behaviour and health in adults: an overview of systematic reviews. Appl Physiol Nutr Metab. 2020;45(10):s197–217.

25. Bailey DP, Withers TM, Goosey-Tolfrey VL, Dunstan DW, Leicht CA, Champion RB, et al. Acute effects of breaking up prolonged sedentary time on cardiovascular disease risk markers in adults with paraplegia. Scand J Med Sci Sports. 2020;30(8):1398–1408.

26. Bredin SS, Jamnik V, Gledhil N, Wartburton DE. Effective pre-participation screening and risk stratification. In: Warburton DE, editor. Health-related exercise prescription for the qualified exercise professional. 6th ed. Vancouver: Health & Fitness Society of BC; 2016. p. 1–30.

27. Arem H, Moore SC, Patel A, Hartge P, Berrington de Gonzalez A, Visvanathan K, et al. Leisure Time Physical Activity and Mortality: A Detailed Pooled Analysis of the Dose-Response Relationship. JAMA Intern Med. 2015;175(6):959–967.

28. Warburton DE, Bredin SS. Reflections on physical activity and health: what should we recommend? Can J Cardiol. 2016;32(4):495–504.

29. Knox ECL, Webb OJ, Esliger DW, Biddle SJH, Sherar LB. Using threshold messages to promote physical activity: implications for public perceptions of health effects. Eur J Public Health. 2013;24(2):195–199.

30. Mercer K, Li M, Giangregorio L, Burns C, Grindrod K. Behavior Change Techniques Present in Wearable Activity Trackers: A Critical Analysis. JMIR mHealth uHealth. 2016;4(2).

31. Mateo GF, Granado-Font E, Ferré-Grau C, Montana-Carreras X. Mobile phone apps to promote weight loss and increase physical activity: a systematic review and meta-analysis. J Med Internet Res. 2015;17(11).

32. Carrington P, Chang K, Mentis H, Hurst A. "But, I don't take steps": Examining the inaccessibility of fitness trackers for wheelchair athletes. ASSETS 2015 - Proc 17th Int ACM SIGACCESS Conf Comput Access. 2015;193–201.

33. Maijers MC, Verschuren O, Stolwijk-Swüste JM, van Koppenhagen CF, de Groot S, Post MWM. Is Fitbit Charge 2 a feasible instrument to monitor daily physical activity and handbike training in persons with spinal cord injury ? A pilot study. Spinal Cord Ser Cases. 2018;4(84). [doi:10.1038/s41394-018-0113-4]

34. Glasheen E, Domingo A, Kressler J. Accuracy of Apple Watch fitness tracker for wheelchair use varies according to movement frequency and task. Ann Phys Rehabil Med. 2021;64(1). [doi:10.1016/j.rehab.2020.03.007]

35. Ogbanufe O, Gerhart N. Watch It! Factors Driving Continued Feature Use of the Smartwatch. Int J Human–Computer Interact. 2018;34(11):999–1014. [doi:10.1080/10447318.2017.1404779]

36. Moreno D, Glasheen E, Domingo A, van Panaligan B, Penaflor T, Rioveros A, et al. Validity of Caloric Expenditure Measured from a Wheelchair User Smartwatch. Int J Sports Med. 2020;41:505–511.

37. Nightingale TE, Rouse PC, Thompson D, Bilzon JLJ. Measurement of Physical Activity and Energy Expenditure in Wheelchair Users : Methods , Considerations and Future Directions. 2017;

38. Ma C, Gravina R, Li Q, Zhang Y, Li W, Fortino G. Activity recognition of wheelchair users based on sequence feature in time-series. In: IEEE International Conference on Systems, Man, and Cybernetics. 2017. p. 3659–3664.

39. Holmlund T, Ekblom-bak E, Franzén E, Hultling C, Wahman K. Defining accelerometer cut-points for different intensity levels in motor-complete spinal cord injury. Spinal Cord. 2020;58:116–124. [doi:10.1038/s41393-019-0308-y]

40. Shwetar Y, Huang Z, Veerubhotla A, Knezevic S, Hong E, Spungen AM, et al. Predicting physical activity intensity using raw accelerometer signals in manual wheelchair users with spinal cord injury. Spinal Cord. 2022;60:149–156.

41. Popp WL, Richner L, Brogioli M, Wilms B, Spengler CM, Curt AEP, et al. Estimation of Energy Expenditure in Wheelchair-Bound Spinal Cord Injured Individuals Using Inertial Measurement Units. 2018;9:1–15.

42. Nightingale TE, Walhim J-P, Thompson D, Bilzon JLJ. Predicting Physical Activity Energy Expenditure in Manual Wheelchair Users. Med Sci Sport Exerc. 2014;46(9):1849–1858.

43. Tsang K. Using wearable sensors for physical acitvity measurement and promotion in wheelchair users. University of Pittsburgh; 2018.

44. Shwetar YJ, Veerubhotla AL, Huang Z, Ding D. Comparative validity of energy expenditure prediction algorithms using wearable devices for people with spinal cord injury. Spinal Cord. 2020;58:821–830. [doi:10.1038/s41393-020-0427-5]

45. O'Driscoll R, Turicchi J, Beaulieu K, Scott S, Matu J, Deighton K, et al. How well do activity monitors estimate energy expenditure? A systematic review and meta-analysis of the validity of current technologies. Br J Sports Med. 2020;54(6):332–340.

46. Carpenter A, Frontera A. Smart-watches: a potential challenger to the implantable loop recorder? EP Eur. 2016;18(6):791–793.

47. Jia W, Wang W, Wen D, Liang L, Gao L, Lei J. Perceived user preferences and usability evaluation of mainstream wearable devices for health monitoring. PeerJ. 2018;6.

48. Niknejad N, Binti W, Mardani A, Liao H, Ghani I. A comprehensive overview of smart wearables: The state of the art literature , recent advances , and future challenges. Eng Appl Artif Intell. 2020;90. [doi:10.1016/j.engappai.2020.103529]

49. European Union. What is GDPR, the EU's new data protection law? 2018 [cited 2022 Mar 7]. URL: https://gdpr.eu/what-is-gdpr/

50. Shaw J, Agarwal P, Desveaux L, Palma DC, Stamenova V, Jamieson T. Beyond "implementation": digital health innovation and service design. npj Digit Med. 2018;1(48).

51. Aitken M, Clancy B, Nass D. The Growning Value of Digital Health - Evidence and Impact on Human Health and the Healthcare System. 2017.

52. Grundy Q. A Review of the Quality and Impact of Mobile Health Apps. Ann Rev Public Heal. 2022;43.

53. Bondaronek P, Alkhaldi G, Slee G, Hamilton F, Murray E. Quality of publicly available physical activity apps: review and content analysis. JMIR mHealth uHealth. 2018;6.

54. Portenhauser AA, Terhorst Y, Schultchen D, Sander LB, Denkinger MD, Stach M, et al. Mobile apps for older adults: systematic search and evaluation within online stores. JMIR Aging. 2021;4(1).

55. Alessa T, Hawley MS, Hock ES, de Witte L. Smartphone apps to support self-management of hypertension: review and content analysis. JMIR mHealth uHealth. 2019;7.

56. Hoevenaars D, Holla JFM, Loo L, Koedijker JM. Mobile App (WHEELS) to Promote a Healthy Lifestyle in Wheelchair Users With Spinal Cord Injury or Lower Limb Amputation : Usability and Feasibility Study. JMIR Form Res. 2021;5(8).

57. Khalil RE, Gorgey AS, Janisko M, Dolbow DR, Moore JR, Gater DR. The role of nutrition in health status after spinal cord injury. Aging Dis. 2013;4(1):14–22.

58. Mollinger LA, Spurr GB, el Ghatit AZ, Barboriak JJ, Rooney CB, Davidoff DD, et al. Daily energy expenditure and basal metabolic rate of patients with spinal cord injury. Arch Phys Med Rehabil. 1985;66(7):420–426.

59. Da Silva Gomes AI, Dos Santos Vigário P, Mainenti MRM, De Figueiredo Ferreira M, Ribeiro BG, De Abreu Soares E. Basal and resting metabolic rates of physically disabled adult subjects: A systematic review of controlled cross-sectional studies. Ann Nutr Metab. 2014;65(4):243–252.

60. Love R, Adams J, van Sluijs EMF, Foster C, Humphreys D. A cumulative meta-analysis of the effects of individual physical activity interventions targeting healthy adults. Obes Rev. 2018;19(8):1164–1172.

61. Rice IM, Rice LA, Motl RW. Promoting Physical Activity Through a Manual Wheelchair Propulsion Intervention in Persons with Multiple Sclerosis. Arch Phys Med Rehabil. 2015;96(10):1850–1858. [doi:10.1016/j.apmr.2015.06.011]

62. Fjeldsoe B, Neuhaus M, Winkler E, Eakin E. Systematic Review of Maintenance of Behavior Change Following Physical Activity and Dietary Interventions. Heal Psychol. 2011;30(1):99–109.

63. Mönninghoff A, Kramer JN, Hess AJ, Ismailova K, Teepe GW, Car LT, et al. Long-term Effectiveness of mHealth Physical Activity Interventions: Systematic Review and Meta-analysis of Randomized Controlled Trials. J Med Internet Res. 2021;23(4).

64. World Health Organization. Global Action Plan on Physical Activity 2018-2030: More Active People for a Healthier World. Geneva, Switzerland; 2018.

65. Rimmer JH, Marques AC. Physical activity for people with disabilities. Lancet. 2012;380(9838):193–195.

66. Martin Ginis KA, Ma JK, Latimer-Cheung AE, Rimmer JH. A systematic review of review articles addressing factors related to physical activity participation among children and adults with physical disabilities. Health Psychol Rev. 2016;10(4):478–494.

67. Smith DM, Duque L, Huffman JC, Healy BC, Celano CM. Text message interventions for physical activity: a systematic review and meta-analysis. Am J Prev Med. 2020;1:142–151.

68. Schoeppe S, Alley S, Van Lippevelde W, Bray NA, Williams SL, Duncan MJ, et al. Efficacy of interventions that use apps to improve diet, physical activity and sedentary behaviour: A systematic review. Int J Behav Nutr Phys Act. 2016;13(1). [doi:10.1186/s12966-016-0454-y]

English summary

Wheelchair users with a chronic disability show on average lower physical activity levels, poorer diet choices, and worse sleep quality, resulting in an unhealthy lifestyle. An unhealthy lifestyle is causing an increased likelihood of obesity and a low level of physical fitness and its corresponding health risks like cardiovascular disease, diabetes and cancer and a lower quality of life. The general introduction in **chapter 1** describes how the lifestyle factors physical activity, diet and sleep are intertwined and what their effect is on physical fitness and health. Furthermore, the general introduction states why healthy lifestyle promotion is especially important in wheelchair users with a chronic disability. Tools to support a healthy lifestyle can be found in mHealth and wearable technology. Optimalization of these tools involve careful planning and design to integrate evidence-based behavior change techniques. In this chapter the value and potential of mHealth, wearable technology and the combination of both is described, and how this can strengthen the intervention effect.

The findings in **Chapter 2** once more emphasize the necessity of the promotion of exercise in people with spinal cord injury (SCI). The aims of chapter 2 were: 1) to estimate the proportion of Dutch wheelchair users with chronic SCI meeting two different exercise guidelines; 2) to evaluate which demographic and lesion characteristics are associated with meeting these guidelines; and 3) whether meeting these guidelines is associated with better physical fitness and health. Whether a participant met the SCI specific exercise guidelines or not, was based on items 4 – 6 of the Physical Activity Scale for Individuals with Physical Disabilities questionnaire. Results of 358 included participants showed that only 63 percent met the least strenuous SCI exercise guidelines without taking strength exercise into account, suggesting that 37 percent is barely or not at all involved in any form of exercise. When taking strength exercise into account, the proportion of participants meeting the least strenuous guidelines was reduced to only 29 percent. This indicates that it is difficult to combine both aerobic and strength exercises on a weekly basis for people with SCI. As expected, based on previous research, older age, being female, having a tetraplegia and low educational level are negatively associated with exercise behavior. It is encouraging to see that meeting the exercise guidelines, and thus increasing aerobic exercise levels, is associated with improved physical fitness and body composition. These results support the theory that any amount of exercise is beneficial, which is suggested in the new World Health Organization physical activity guidelines, as fairly low levels of weekly aerobic exercise were already associated with improved physical fitness. The evidence-based exercise guidelines for people with SCI seem to partly achieve what they are designed for and should, therefore, be used as a guideline for physical activity and health promotion.

An often used mode of physical activity promotion are activity trackers. Heart rate (HR) registration is an important parameter because it is used in many functions available in activity trackers, e.g. energy estimation, exercise intensity and estimation of activity levels. The aims of **Chapter 3** were to investigate 1) the HR accuracy measured with photoplethysmography (PPG) with a Fitbit Charge 2 in wheelchair users with SCI, 2) how the activity intensity affects HR accuracy, and 3) whether this HR accuracy is affected by lesion level. HR of 34 participants with SCI were measured both with the Fitbit Charge 2 and Polar H7 chest strap simultaneously during rest, wheelchair activities and strength exercises and compared with data of 10 participants without SCI. To investigate the device accuracy, the mean absolute error (MAE), mean absolute percentage error (MAPE) and concordance correlation coefficients (CCC) were determined. In addition, Bland-Altman plots and 95% limits of agreement were produced. Results showed that the HR accuracy is in general lower in people with SCI compared to able-bodied. Results showed a worse accuracy than the acceptable MAPE of ± 10% and worsened in increasing activity intensities. Furthermore, accuracy severely dropped in people with tetraplegia (lesions levels above T1), specifically during wheelchair activities and strength exercise. This reduction in accuracy is most likely caused due to the PPG technique applied to measure HR with activity trackers. HR registration with the PPG technique is influenced by blood pressure regulation, which is often altered in people with SCI due to an imbalance of the sympathetic and parasympathetic system, with higher lesions showing a larger imbalance. Therefore, PPG-based HR measurements should be taken with caution in people with tetraplegia, especially when the importance of accurate data is high.

In **chapter 4**, the aims were to describe the developmental process of the WHEELS lifestyle application (app) and the results of a usability and feasibility study. The WHEELS lifestyle app was developed using the intervention mapping framework for planning theory and evidence-based health promotion programs. This chapter is particularly focusing on step 1 to 4 (1) perform needs assessment and state intervention goals, 2) construct matrices of change objectives, 3) choose theory and evidence-based behavior change methods and 4) corresponding practical app features to deliver them and pretest, refine, and produce the program), respectively. Subsequently, a pilot-study was conducted to evaluate the usability and feasibility of the WHEELS lifestyle app and explore its effectiveness. Participants were invited for a 12-week pre-post pilot study in which participants either received remote-guidance from a lifestyle coach or were allocated to the stand-alone group and received no guidance. Lifestyle-related outcomes on physical activity, nutrition, sleep quality, body composition and other secondary outcomes were measured pre and post intervention. After finishing the intervention, participants were invited for an exit-interview. In total 14 wheelchair users with either SCI or lower limb amputation finished the 12-week usability and feasibility study. The results from the exit-interview showed varied user experience. With a below average system usability score of 58.6, there was room for improvement. Promising results were found on the intervention effect of the WHEELS lifestyle app. A significant reduction in waist circumference and percentage fat mass were found, and an increase in percentage fat-free mass. Positive trends were found in body mass, daily grams of fat consumed and sleep quality. Overall the WHEELS app scored reasonable on usability and showed room for improvement. The outcomes showed promising results and seemed feasible to deploy on a larger scale.

In follow up of the pilot-study, changes were applied to the WHEELS lifestyle app to improve its usability and allow integration of an activity tracker. With the integration of an activity tracker, additional modes of delivery of behavior change techniques were included and could lead, together with the improvement in usability, to better results. The aims in **chapter 5** were, therefore, to determine changes in physical activity, nutrition, sleep behavior, and body composition on a larger scale in inactive wheelchair users with a chronic disability. In addition, the aim was to explore whether a shift in stage of change is related to actual behavior change. Thirty wheelchair users with a chronic disability were included in a 12-week pre-post intervention study design, starting with a 1-week control period. During the intervention, participants were able to consult a lifestyle coach within the WHEELS app for lifestyle-related questions and app support. Throughout the intervention, participants wore a Fitbit Charge 3 activity tracker which continuously measured lifestyle-related outcomes. Self-administered lifestyle-related measurements were administered pre- and postintervention on physical activity, nutrition, sleep quality, body composition, health-related quality of life and stage of change on physical activity and nutrition. Results showed improved nutrition behavior with a significant reduction in total energy, fat and protein intake. Participants reported a significant reduced body mass, body mass index and waist circumference after the 12-week intervention period. However, no significant lasting changes were found on physical activity behavior and sleep quality based on the Fitbit data. Improved body satisfaction, mental health and vitality were experienced as well as a reduced experienced fatigue. No interaction was found between stage of change and behavior change on physical activity and sleep based on Fitbit data, suggesting one question about the readiness for behavior change could not verify actual change. Based on the results, it can be concluded that the WHEELS app is a valuable and easy tool to support healthy lifestyle behavior in wheelchair users in a home setting.

In **chapter 6** the main findings of the thesis are summarized and it is discussed what they collectively contribute to the knowledge on healthy lifestyle in wheelchair users with a chronic disability. A broader view on promoting physical activity, wearable use in wheelchair users and mHealth is given, together with the clinical implications of the findings in this thesis.

Opportunities and suggestions for future research are discussed, which could lead to new insights on healthy lifestyle promotion in wheelchair users.

Nederlandse samenvatting

Rolstoelgebruikers met een chronische aandoening hebben gemiddeld een lager fysiek activiteitenniveau, laten een slechter eetpatroon zien en hebben een slechter slaap kwaliteit dan valide mensen, resulterend in een ongezonde leefstijl. Een ongezonde leefstijl draagt bij aan een verhoogde kans op obesitas en een slechte fysieke fitheid en de daarbij horende gezondheidsrisico's zoals cardiovasculaire aandoeningen, diabetes en verschillende vormen van kanker en een lagere kwaliteit van leven. The algemene introductie in **hoofdstuk 1** beschrijft hoe de leefstijlfactoren fysieke activiteit, dieet en slaap in elkaar verweven zijn en wat de invloed van deze factoren op gezondheid is. Verder wordt er beschreven waarom het promoten van een gezonde leefstijl extra belangrijk is voor rolstoelgebruikers met een chronische aandoening. Hulpmiddelen ter ondersteuning van een gezonde leefstijl kunnen gevonden worden in de vorm van mHealth en draagbare technologie. Het optimaliseren van deze hulpmiddelen ter ondersteuning van een gezonde leefstijl vraagt een nauwkeurige planning en ontwerp om wetenschappelijk bewezen gedragsveranderingstechnieken correct toe te passen. In hoofdstuk 1 is de waarde en het potentieel van mHealth, draagbare technologie, de combinatie van beiden, en hoe dit het interventie effect kan verbeteren beschreven.

De resultaten in **hoofdstuk 2** benadrukken nogmaals de noodzaak om fysieke activiteit te promoten bij mensen met een dwarslaesie. De doelen in hoofdstuk 2 waren: 1) het schatten welke proportie van de Nederlandse rolstoelgebruikers met een chronische dwarslaesie de twee dwarslaesie specifieke beweegrichtlijnen behalen; 2) te evalueren welke demografische en laesie karakteristieken geassocieerd zijn met het behalen van deze beweegrichtlijnen; en 3) of het behalen van deze richtlijnen geassocieerd is met een betere fitheid en gezondheid. Of de dwarslaesie specifieke beweegrichtlijnen werden behaald of niet, werd gebaseerd op vragen 4 – 6 van de "Physical Activity Scale for Individuals with Physical Disabilities" vragenlijst. Resultaten van 358 deelnemers lieten zien dat slechts 63 procent de minst intensieve beweegrichtlijn behaalde wanneer krachttraining buiten beschouwing werd gelaten, suggererend dat 37 procent niet of nauwelijks betrokken is in enige vorm van training. Wanneer krachttraining wel meegenomen werd, was de proportie van de deelnemers dat voldeed aan de minst intensieve beweegrichtlijn gereduceerd naar 29 procent. Dit duidt erop dat het lastig is voor mensen met een dwarslaesie om aerobische training te combineren met krachttraining op wekelijkse basis. Zoals verwacht, gebaseerd op eerdere literatuur, lieten de resultaten zien dat een oudere leeftijd, vrouw zijn, een tetraplegie hebben en een laag opleidingsniveau negatief geassocieerd zijn met wekelijkse trainingstijd. Het is bemoedigend om te zien dat het voldoen aan de beweegrichtlijnen geassocieerd is met een betere fysieke fitheid en lichaamssamenstelling. De resultaten ondersteunen de theorie dat elke mate van training voordeel oplevert, wat aangeraden wordt door de beweegrichtlijnen van de wereld gezondheidsorganisatie (WHO), aangezien een relatief laag wekelijks aerobisch trainingsniveau al geassocieerd was met een toename in fysieke fitheid. De wetenschappelijke beweegrichtlijnen specifiek voor mensen met een dwarslaesie lijken gedeeltelijk waar te maken waar ze voor ontwikkeld zijn, en dienen daarom gebruikt te worden ter ondersteuning van het promoten van fysieke activiteit.

Een regelmatig gebruikte methode voor het promoten van fysieke activiteit zijn activiteiten trackers. Hartslag registratie is een belangrijke parameter aangezien deze gebruikt wordt in vele functies die aanwezig zijn in een activiteiten tracker, zoals energieschatting, bepalen van trainingsintensiteit, en schatting van dagelijkse activiteiten niveau. De doelen in **hoofdstuk 3** waren om te onderzoeken 1) wat de nauwkeurigheid is van de hartslag registratie gemeten met fotoplethysmografie (PPG) met een Fitbit Charge 2 bij rolstoelgebruikers met een dwarslaesie; 2) hoe de intensiteit van activiteit de nauwkeurigheid van de hartslagregistratie beïnvloed; en 3) of de nauwkeurigheid van de hartslagregistratie beïnvloed wordt door de laesie hoogte van de dwarslaesie. De hartslag van 34 rolstoelgebruikers met een dwarslaesie is tegelijk gemeten met zowel een Fitbit Charge 2 als een Polar H7 borstband tijdens rust, rolstoelactiviteiten en krachttraining en vergeleken met de resultaten van 10 deelnemers zonder een dwarslaesie. Om de nauwkeurigheid te onderzoeken zijn de gemiddelde absolute foutmarge (MAE), percentage van de gemiddelde absolute foutmarge (MAPE) en overeenkomst correlatiecoëfficiënt (CCC) bepaald. In aanvulling zijn er Bland-Altman plots met 95% limieten geproduceerd. De resultaten lieten zien dat de hartslag nauwkeurigheid in het algemeen slechter is bij mensen met een dwarslaesie ten opzichte van de mensen zonder dwarslaesie. De resultaten lieten een slechtere nauwkeurigheid zien dan de acceptabele MAPE van ± 10% en verslechterde bij toenemende intensiteit. Daarnaast was er een duidelijke verdere afname in nauwkeurigheid te vinden bij mensen met een tetraplegie (laesie boven thoracaal 1), met name tijdens de rolstoelactiviteiten en krachttraining. Deze afname in nauwkeurigheid is hoogstwaarschijnlijk veroorzaakt door de PPG techniek die toegepast wordt om de hartslag te meten in activiteiten trackers. Hartslag registratie met de PPG techniek wordt beïnvloed door bloeddruk regulatie, welke bij mensen met een dwarslaesie aangedaan is door een disbalans tussen het sympathisch en parasympatisch systeem van het autonome zenuwstelsel. Bij mensen met een hogere laesie, is de disbalans tussen deze systemen vaak groter. Om deze reden zouden hartslag metingen met PPG met voorzichtigheid geïnterpreteerd worden bij mensen met een dwarslaesie, zeker bij mensen met een tetraplegie, wanneer het belang van accurate data hoog is.

De doelen In **hoofdstuk 4** waren om het ontwikkel proces van de WHEELS leefstijl applicatie (app) en de resultaten van een bruikbaarheid en haalbaarheid onderzoek te beschrijven. De WHEELS leefstijl app was ontwikkelend met behulp van de zogenoemde ‘intervention mapping framework' voor het plannen van theorie en wetenschappelijk onderbouwde gezondheidsbevorderingsprogramma's. Dit hoofdstuk heeft zich voornamelijk gericht op stap 1 tot 4: 1) een evaluatie van de behoeftes en interventie doelen opstellen, 2) opzetten van matrices van doelstellingen; 3) selecteren van theorie en wetenschappelijk onderbouwde gedragsverandering technieken en bijhorende praktische toepassing hiervan en 4) het uittesten, verbeteren en afmaken van het programma. Daaropvolgend is er een pilotstudie uitgevoerd om de bruikbaarheid en haalbaarheid van de WHEELS app te evalueren en een eerste inzicht te krijgen in het interventie effect. Deelnemers waren uitgenodigd voor een 12 weken durende pilotstudie waarin deelnemers of begeleiding op afstand hebben ontvangen van een leefstijlcoach, of volledig zelfstandig met de app aan de slag zijn gegaan. Leefstijl gerelateerde uitkomsten op de aspecten fysieke activiteit, dieet, slaap kwaliteit, lichaamssamenstelling en andere bijhorende aspecten waren voor en na de interventie gemeten. Na de afronding van de interventie zijn deelnemers uitgenodigd voor een afsluitende interview. In totaal hebben 14 deelnemers met een dwarslaesie of onderste been amputatie(s) deelgenomen aan het onderzoek. De resultaten van het afsluitende interview laten gemixte gebruikerservaringen zien. Met een onder gemiddelde 'system usability score' van 58.6 was er ruimte voor verbetering. De resultaten liet een veelbelovend interventie effect zien van de WHEELS leefstijl app. Een significante afname in buikomvang en vetpercentage was gemeten, gepaard met een toename in het percentage vetvrije massa. Positieve trends waren gevonden in de ontwikkeling van het lichaamsgewicht, dagelijks geconsumeerde hoeveelheid gram vet en in slaap kwaliteit. In het geheel scoorde de WHEELS leefstijl app redelijk op gebruiksvriendelijkheid en liet ruimte voor verbetering zien. De uitkomsten lieten veelbelovende resultaten zien en leek haalbaar om op grotere schaal uit te zetten.

In vervolg op de pilotstudie zijn er aanpassingen doorgevoerd in de WHEELS leefstijl app om de gebruikerservaring te verbeteren en de integratie van een activiteiten tracker te bewerkstelligen. Met de integratie van een activiteiten tracker worden gebruikers op additionele manieren blootgesteld aan gedragsveranderingstechnieken en zou op deze wijze, samen met de toegenomen gebruiksvriendelijkheid, kunnen leiden tot een verbeterd interventie effect. De doelen van **hoofdstuk 5** waren daarom, om verandering in het gedrag van fysieke activiteit, dieet, slaap gedrag, en lichaamssamenstelling te bepalen bij een grotere groep inactieve rolstoelgebruikers met een chronische aandoening. In aanvulling is onderzocht of een verandering in 'stage of change', waarin de bereidbaarheid voor gedragsverandering wordt uitgevraagd, gerelateerd is aan daadwerkelijk gedragsverandering. 30 rolstoelgebruikers met een chronische aandoening zijn geïncludeerd in een 12 weken durend onderzoek, met voorafgaand een controle periode van één week. Tijdens de interventie konden deelnemers een leefstijlcoach consulteren in de WHEELS leefstijl app voor leefstijl gerelateerde vragen en app ondersteuning. Gedurende het gehele onderzoek droegen deelnemers continu een Fitbit Charge 3 activiteiten tracker om leefstijl gerelateerde uitkomsten te meten. Voor en na de interventie periode hebben deelnemers zelf metingen afgenomen gericht op fysieke activiteit, dieet, slaap kwaliteit, lichaamssamenstelling, gezondheid gerelateerde kwaliteit van leven en 'stage of change' van fysieke activiteit en dieet. Resultaten lieten een verbeterd dieet gedrag zien met een afname in totale energie, vet en proteïne inname. Deelnemers rapporteerden een afname in lichaamsgewicht, body mass index en buikomvang na de interventie periode van 12 weken. Echter zijn er geen blijvende veranderingen gemeten in het beweeg en slaapgedrag gebaseerd op de Fitbit data. Een verbeterde zelfbeeld, mentale gezondheid en vitaliteit was ervaren gepaard met een afname in ervaarde vermoeidheid. Er was geen interactie effect gevonden tussen 'stage of change' en het getoonde gedrag in fysieke activiteit en dieet, wat suggereert dat één vraag over de bereidbaarheid voor gedragsverandering niet daadwerkelijke gedragsverandering kan verifiëren. Gebaseerd op de resultaten kan geconcludeerd worden dat de WHEELS leefstijl app een waardevolle en gemakkelijk hulpmiddel is om een gezonde leefstijl te promoten in rolstoelgebruikers in een thuisomgeving.

In **hoofdstuk 6** worden de belangrijkste bevindingen van het proefschrift samengevat en bediscussieerd wat ze gezamenlijk toevoegen aan de kennis over gezonde leefstijl bij rolstoelgebruikers met een chronische aandoening. Een bredere beschouwing op het promoten van fysieke activiteit, draagbare technologie bij rolstoelgebruikers en mHealth is beschreven, samen met de klinische implicaties van de bevindingen van dit proefschrift. Kansen en suggesties voor toekomstig onderzoek worden benoemd, welke tot nieuwe inzichten kunnen leiden over het promoten van gezonde leefstijl in rolstoelgebruikers met een chronische aandoening.

Dankwoord

Aangezien het dankwoord vaak het meest gelezen stuk van het gehele proefschrift is (volgens vele mede-PhD'ers en sprekend uit eigen ervaring), zou je verwachten dat de ervaren druk het grootst is en hier de meeste tijd in gestoken zou moeten worden, maar gelukkig is dat niet het geval. Naast dat ikzelf veel tijd in mijn proefschrift heb gestoken, hebben veel supervisors, collega's en deelnemers aan de verschillende onderzoeken direct of indirect tijd in mij gestoken die ik hiervoor zeer dankbaar ben.

Thomas, als penvoerder en PI van het onderzoeksproject wil ik je bedanken voor de kans die je mij hebt gegeven binnen de VU en Reade. Hoewel het gehele project mogelijk wat anders uit heeft gepakt dan initieel gepland, denk ik dat er waardevol onderzoek heeft plaatsgevonden en het resultaat er mag zijn. Ik heb veel mogen leren van je kritische blik en scherpe opmerkingen.

Een uitspraak die ik vaker gedaan heb in gesprek met collega's is "Ik gun iedereen een Sonja in je promotieteam". Sonja, de snelheid en helderheid van je feedback die ik heb mogen ervaren hebben mogelijk enkele extra maanden gescheeld in de duur van mijn PhD, terwijl er daarnaast vaak ook nog ruimte was voor een persoonlijk gesprek. Bedankt voor alle tijd, aandacht en geduld die je voor mij gehad hebt, zowel werk als niet werk gerelateerd.

Hoewel je later pas binnen het project officieel een rol als copromotor kreeg, heb ik vanaf het begin meteen veel gehad aan je betrokkenheid als supervisor. Jasmijn, als nauw betrokkene bij de ontwikkeling en inzet van de WHEELS app heb ik inhoudelijk veel hulp gehad en veel van je geleerd. Bedankt voor het vele meedenken en de prettige samenwerking.

Wessel, hoewel er een grote afstand tussen ons zat, zowel fysiek als wat betreft het onderwerp data science, waar ik maar beperkt bekend mee was, was je altijd makkelijk benaderbaar wanneer ik dit nodig achtte. Hoewel er gedurende de jaren van het project veel is gebeurd, zowel binnen als buiten het project, bleef je altijd op de achtergrond betrokken. Bedankt voor je steun, inzet en feedback.

Al is het maar een korte periode geweest dat jij, Marije, betrokken bent geweest als copromotor, wil ik je bedanken voor de prettige start en samenwerking die we hebben gehad.

Iris, and previously Ricardo, as the data science postdoc within the project, it has been interesting involving me in an aspect of science I was not so familiar with. Over time I got to learn a thing or two about data science and always enjoyed our discussions. Although the data science aspect of the project might have been smaller than initially planned, the collaboration has been congenial and I thank you for that.

Zonder deelnemers geen onderzoek, zonder onderzoek geen proefschrift. Daarom wil ik alle deelnemers bedanken voor alle tijd en moeite die jullie vrijwillig in de verschillende onderzoeken hebben gestoken. De bereidheid en het enthousiasme van jullie deelname deed mij goed en het contact met jullie liet mij vaak de waarde van het onderzoek van dichtbij zien, dank hiervoor!

Toen ik mijn PhD begon aan de VU, wist ik eigenlijk niets af van de afdeling Bewegingswetenschappen en had ik geen flauw benul wat ik er kon verwachten. Dat ik de afgelopen jaren zo heb mogen ervaren met alle collega's die komen en gaan had ik vooraf niet gedacht. Sabrina, Coen, mooi dat ik mijn hele PhD periode aan de VU (en geregeld daarbuiten) samen met jullie heb mogen meemaken. Dat ik dit afsluit met jullie aan mijn zijde als paranimfen maakt het extra mooi. Hoewel onze gezamenlijke periode bij de VU stopt, zullen wij elkaar zeker blijven zien!

Spontane borrels, beachvolleybal, PhD activiteiten en weekenden, festivals, stap avonden, koffie pauzes, congres bezoeken en geregeld bij collega's thuis over de vloer, het gebeurde met regelmaat in de afgelopen jaren. Activiteiten die met regelmaat gedaan zijn met Sabrina, Coen, Koen, Puck, Niels, Ton, Bart, Erik, Mireille, Lisa, Roel, Guido, Anouk, Ruud, Anne, Moira, Nina, Lisa, Guido, Ilse, Laure, Ingrid, Tammie, Annelies, Daphne. Maar ook oud collega's zoals Nick, Lotte, Stephan, Jeanine, Twan, Annike, Stephanie, Anna, Jennifer, Axel, Wieke. Bedankt voor de gezellige tijd en inhoudelijke discussies die ik de afgelopen jaren met jullie heb ervaren.

I would like to specifically mention that I have always enjoyed the international oriented environment at the department of human movement sciences. Introducing, comparing and exchanging different cultures with each other has always been incredibly fun, interesting and often resulted in hilarious situations and definitely enriched the environment within and outside the department. Emily, Ali, Sauvik, Mohammad, Rafael, Margit, Daniel (2x), Nicola, Leila, Yiming, Andrea, Marzieh, thank you all for the fun times together and learning me a thing or two about your culture.

En 'nieuwe' collega's die niet meer zo nieuw zijn waar ik, met veel plezier, post-covid helaas maar enkele activiteiten mee heb mogen ervaren. Daardoor weet ik zeker dat de sfeer voorlopig nog wel goed zal blijven op de afdeling, Jens, Marit, Bart, Pieter, Maaike, Lotte, veel succes nog de komende jaren.

Opvallend voor mij was om te horen dat andere PhD'ers in compleet andere werkvelden tijdens zo'n promotietraject tegen dezelfde dingen aanlopen en worstelen met vergelijkbare uitdagingen. Bas, Marten, het was altijd leuk om de zin (en naar onze mening soms onzin) zaken van een PhD te vergelijken. Maar vooral ook te hebben over totaal niet PhD gerelateerde zaken, met regelmatig een ver ondermaats gespreksniveau.

Het werd nog leuker wanneer je de uitdagingen besprak met vrienden die niet bekend zijn zo'n promotietraject, wat relativeren en afstand nemen van het werk een stuk makkelijker maakt. De waarde (en in mijn mening noodzaak) hiervan mag niet onderschat worden. (ex-)Groningers Danny (Fortuna!), Wiebren, Ronald, Jelle, Justa, Domien/Rob, Marco, Koen, Aaldries, Wiebo, Nienke, Bart, Janne, Klaske, Kelly, Carmen en Michiel. De weekendjes weg, uit de hand gelopen spelavonden, spontane clubavonden, festivals, trainingen en avonden zonder eind maken het dat ik nog geregeld met plezier de reis naar het noorden maak en zal blijven maken.

Last maar zeker niet least, familie Hoevenaars. Judith, Teun, Joost, Marta, Lori en Malou, hoewel de frequentie dat we elkaar zien sterk varieert en niet altijd hoog ligt, maakt dat het plezier en belang hiervan niet minder op. Teun en Judith, als ik jullie niet als voorbeeld had gehad weet ik niet of ik mezelf intellectueel zo was blijven uitdagen, hierin zijn jullie altijd een inspiratie voor mij geweest. Henriëtte, Ton, de rol die jullie betekend hebben voor mij, dat onder andere heeft geleid tot de totstandkoming van dit proefschrift, is moeilijk te beschrijven. De vrijheid en steun die jullie altijd gegeven hebben in mijn opleidingen, sport en persoonlijke ontwikkeling ben ik jullie ontzettend dankbaar. De deur staat altijd open voor mij, maar zoals al meerdere vrienden en collega's hebben mogen ervaren ook voor vele anderen. Met plezier probeer ik dat voorbeeld tot de dag van vandaag te volgen.

List of publications

Publications as part of this thesis

Hoevenaars D, Holla J, te Loo L, Koedijker J, Dankers S, Houdijk H, Visser B, Janssen T, de Groot S, Deutekom M, WHEELS Study Group. Mobile app (WHEELS) to promote a healthy lifestyle in wheelchair users with spinal cord injury or lower limb amputation: usability and feasibility study. JMIR Form Res 2021;5(8):e24909. DOI: 10.2196/24909.

Hoevenaars D, Yocarini IE, Paraschiakos S, Holla JFM, de Groot S, Kraaij W, Janssen TWJ. Accuracy of Heart Rate Measurement by the Fitbit Charge 2 During Wheelchair Activities in People With Spinal Cord Injury: Instrument Validation Study. JMIR Rehabil Assist Technol 2022;9(1):e27637. DOI: 10.2196/27637.

Hoevenaars D, Holla JFM, Postma K, van der Woude LHV, Janssen TWJ, de Groot S. Associations between meeting exercise guidelines, physical fitness, and health in people with spinal cord injury, Disability and Rehabilitation 2022, DOI: 10.1080/09638288.2022.2048910.

Hoevenaars D, Holla JFM, de Groot S, Weijs PJM, Kraaij W, Janssen TWJ. Lifestyle and health changes in wheelchair users with a chronic disability after 12 weeks of using the WHEELS mHealth application. Disability and Rehabilitation: Assistive Technology 2022, DOI: 10.1080/17483107.2022.2115563.

Other publications

van Ark M, Rabello LM, **Hoevenaars D**, Meijerink J, van Gelderen N, Zwerver J, van den Akker-Scheek I. Inter- and intra-rater reliability of ultrasound tissue characterization (UTC) in patellar tendons. Scand J Med Sci Sports. 2019 Aug;29(8):1205-1211. DOI: 10.1111/sms.13439.

Ma Y, de Groot S, **Hoevenaars D**, Achterberg W, Adriaansen J, Weijs PJM, Janssen TWJ. Predicting resting energy expenditure in people with chronic spinal cord injury. Spinal Cord 2022, DOI: 10.1038/s41393-022-00827-5.