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Original Research

Observing the Relationship Between Additional Measures of Handgrip Strength and the 6-Minute Push Test in Ambulatory Young Adults

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Abstract

International Journal of Exercise Science 18(5): 170-181, 2025. https://doi.org/10.70252/MTMZ3396 Manual wheelchair users have been shown to have low functional capacity and limited ability to perform activities of daily living. Conventional protocols for assessing physical attributes such as muscle function in this population have unique boundaries such as expensive testing equipment and procedures not specific to wheelchair propulsion. The measurement of muscle function using electronic handgrip dynamometry has shown promise in assessing additional characteristics beyond strength capacity alone. This study aimed to determine the correlations of electronic handgrip dynamometry derived strength, time to peak force generation, fatigability (22.40±10.12%), isometric control, and asymmetry with aerobic capacity in ambulatory young adults. We included 34 recreationally active ambulatory adults aged 23.76±3.57 years. Muscle function was assessed using electronic handgrip dynamometry. Aerobic capacity was examined using the six-minute wheelchair push test (1112.17±92.84ft). Fatigability (22.40±10.12%) showed a significant, near moderate negative correlation (r=-0.345, p<0.05) with push test outcomes, while the correlation with all other measures was not-significant. Our findings show that electronic handgrip dynamometry derived fatigability is related to aerobic capacity in those who use manual wheelchairs. Given the relationships shown in the current study, electronic handgrip dynamometry has promise for assessing functional health in persons with disabilities, which has particular relevance for SCI, and could be used in clinical practice and physical medicine and rehabilitation (PM&R) as a tool to examine functional capacity in applicable populations. However, future research is warranted to assess the concurrent validity of the additional measures of handgrip strength assessing muscle function.

Keywords: Hand strength, humans, wheelchair, muscle strength, muscle strength dynamometer, morbidity

Introduction

In the United States, there are roughly 3.6 million Americans that use wheelchairs as mobility aides, including, but not limited to those with spinal cord injuries, multiple sclerosis, and cerebral palsy.[1,2] Conditions deriving from motor function impairments, neurological deficits, and musculoskeletal limitations associated with manual wheelchair users are shown to lead to strain during daily activities. The strain during wheelchair ambulation in household activities limits performing basic self-care tasks.[3] Such strain is due to the predominant overuse of upper limb muscles during wheelchair propulsion.[4] Because of these limitations paired with a greater susceptibility for upper extremity impairments associated with overuse, wheelchair users tend to have low physical health, decreased functional and aerobic capacity, which is a measure of cardiorespiratory fitness and a major component of physical ability.[5–7]

Components of physical capacity, such as aerobic capacity, in wheelchair users are currently assessed in laboratory settings with field tests that have been developed by modifying existing tests used in ambulatory populations.[8,9] Field tests are considered conventional for assessing aerobic capacity in manual wheelchair users. However, in comparison with laboratory protocols, specific boundaries exist and are associated with the cost of specialized equipment, lack of specificity with traditional wheelchair propulsion, and external factors which induce propulsion variability.[9–12] Knowing the limitations of current field tests, the development of a valid and accessible protocol for assessing physical capacity in manual wheelchair users is clinically important.

Handgrip strength (HGS) is a convenient and reliable assessment of strength capacity that is often measured with hydraulic handgrip dynamometry.[13,14] Although HGS protocols and equipment has a long-standing use for health and human performance, only muscle strength is being measured.[15] Electronic handgrip dynamometry has emerged for assessing multiple muscle function attributes beyond strength capacity while preserving feasibility. Such attributes may include asymmetry, fatigability, time to peak force generation, and isometric force control.[16] These additional measures have not been well assessed in manual wheelchair users. Furthermore, it is known that the upper extremities have limited functional capacity and are more fatigable in those who use manual wheelchairs, indicating a possible link between additional measures of muscle function measured with electronic handgrip dynamometry and modified field tests, such as the 6-minute push test (6MPT), a valid and reliable test for assessing aerobic capacity in those who use wheelchairs.[2,17,18]

Therefore, the primary purpose (purpose 1) of this study was to determine the correlations between maximal handgrip strength, time to peak force generation, fatigability, isometric control, and asymmetry and the propulsion outcomes during the 6MPT in ambulatory young adults using wheelchairs. Using ambulatory adults with no prior wheelchair experience allowed for equal wheelchair propulsion experience in all participants to decrease variability in propulsion test outcomes when trying to find the initial relationship with muscle function. A secondary purpose (purpose 2) was to evaluate the relationships between the four additional grip tasks stated above and maximal HGS in young ambulatory adults using wheelchairs. It was hypothesized increased maximal handgrip strength, handgrip rate of force development, handgrip fatigability, handgrip isometric control, and no handgrip asymmetry will be valid predictors for assessing functional capacity measured via the six-minute push test and that there will be a positive correlation between handgrip rate of force development, handgrip isometric control, and handgrip asymmetry on maximal handgrip strength, as well as a negative correlation between handgrip fatiguability and maximal grip strength in young ambulatory adults using wheelchairs.

Methods

Participants

A cross-sectional design was utilized to complete this investigation. The Northern Michigan University Institutional Review Board approved all study protocols (HS23-1374). To account for any missing data and adhere to the recommended minimum number of individuals for 80% power in a single group cross-sectional design to obtain a correlation coefficient of ≥0.50, the researcher recruited 34 participants. Sample size was calculated using a priori power analysis (G Power, Aichach Germany) and collected pilot data consisting of 10 participants. Effect size was set at 0.5 with a power of 0.80. The researcher recruited by word of mouth, email list serves, flyers, and oral presentations.

We recruited individuals between the ages of 18 and 35 years old who met the current physical activity guidelines for Americans[19], and had no prior manual wheelchair experience. Persons were excluded if they 1) had any musculoskeletal injuries, health conditions, or surgical procedures within the last six-months that limited physical functioning (e.g., fractures, sprains, arthritis); 2) were not ready to participate in physical activity as determined by the PAR-Q+[20]; 3) were not ambulatory; or 4) were unable to complete dynamometer testing on both hands due to pain, arthritis, or a surgical procedure. Each session lasted between 30- and 60-minutes in duration.

Protocol

This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science.[21] Participants were recruited by word-of-mouth on Northern Michigan Universities campus. Prior to study testing, individuals were asked to avoid strenuous physical activities for 48 hours prior to their visit and maintain habitual sleeping, eating, and hydration patterns. Participants attended one session that lasted up to 60 minutes, beginning with a review of an informed consent form explaining all aspects of the study prior to taking part in any study procedures. Participants were also asked to complete a PAR-Q+, and the International Physical Activity Questionnaire (IPAQ-SF) to screen for risk associated with performing physical activity and assess physical activity, respectively. Once written informed consent was provided, and if the participant met all inclusion criteria, data collection began with obtaining all measures of HGS. All study protocols were approved by the Northern Michigan University Institutional Review Board.

Gripping tasks were recorded using a Biopac electronic handgrip dynamometer (Biopac Systems; Goleta, CA) and MP36 Student Lab software. Previous research suggests that Biopac handgrip dynamometers are highly reliable and valid for determining handgrip force.[22] The Biopac dynamometer allows for kilograms of force to be digitally recorded in real-time for the duration of a grip task.[23] Guidelines for measuring HGS informed our procedures.[24] Specifically, participants were comfortably seated in a chair with forearms in a 90-degree resting position, wrist neutral, and hand slightly over the arm of the chair with thumbs facing upwards. A trained interviewer explained and demonstrated all handgrip protocols before participants completed a practice trial. Standardized verbal encouragement was provided for all participants. Block randomization was used to determine hand start. Participants performed two trials on both hands for each task at a sampling rate of 50 Hz with a minimum of 60-seconds rest between all assessment trials. All grip tasks were performed in the following order.

For maximal HGS, participants were seated in a chair with their elbow rested at 90-degrees. The trained interviewer advised the participant to squeeze the dynamometer as hard as possible, exhaling while squeezing before releasing the muscle contraction. The greatest recorded HGS value regardless of hand was used for analysis. Next, the time to peak force generation was calculated by instructing the participant to squeeze the dynamometer as fast as possible, and delta t was determined from rest to the single highest-performing measure.[25] The highest-performing continuous score was included for the purposes of the analysis with 60-seconds of rest between trials.

Fatigability was measured next by having participants squeeze the dynamometer at maximal effort for as long as possible or until they could no longer maintain 75% of their maximal effort.[26] A corresponding grip force curve was generated from the collected data. Fatigability was then calculated from the fatigability index equation, which utilizes the area under the curve (kg/s), peak force (kg), and duration of contraction (sec). The equation being used is fatigue index = {1-[area / (peak force * duration)]} * 100.

Isometric control was measured by having the participant squeeze the dynameter at 25% of their maximal value determined by their maximal HGS for each hand for a total of 10-seconds with a force tracing visible to participants. The coefficient of variation was determined over the middle eight-seconds using the best-performing submaximal HGS force control value for analysis. Lastly, the highest recorded HGS values on either hand were used to calculate the asymmetry ratio (non-dominate HGS (kilograms)/dominant HGS (kilograms)). Since asymmetry ratios could be <1.0, any asymmetry ratios <1.0 were inversed to make all ratios ≥1.0 to improve interpretability.[16]

Finally, the 6-Minute Push Test (6MPT) was conducted following all grip tasks on a course consisting of a 30-m loop marked by two cones 15-m apart with 30 in. wide lanes marked between the cones on either side to ensure between-subject reliability. The 6MPT was modeled after the 6-Minute Walk Test (6MWT), therefore, American Thoracic Society (ATS) administration instructions and guidelines for the 6MWT were followed, including the standard patient instruction script.[17] A Quickie 2 manual wheelchair (Quickie Wheelchairs, Phoenix Arizona) was used to conduct the propulsion test. Once in the wheelchair, participants were given five-minutes to become acclimated to wheelchair propulsion and the mechanics of making turns. After the acclimation period, participants rested for an additional five-minutes; once they returned to a near resting state, they were instructed to position themselves at the designated starting position on the test course. At the starting position, a pretest script was used to instruct the participant to propel as far as possible within the six-minute time frame at a comfortable pace as if they were pushing around the grocery store.[10] Participants were also advised that they may slow down or stop at any point during the test but time would not stop until the test was completed or the participant requested to end the test. A stopwatch began the moment the participant began propulsion, and the participants were instructed to stop where they were as soon as the stopwatch reached six-minutes. Total distance was measured by counting the number of laps completed and the distance from the end cone to the stopping point.

Statistical Analysis

SPSS Software version 28.0 (IBM; Armonk, NY) was used for the analyses. Descriptive statistics were reported as mean ± standard deviation for continuous variables or frequency (percentage) for categorical variables. The data were visually inspected for outliers and it was determined that parametric assumptions were met. To accomplish Purpose 1, individual Pearson correlation analyses were used to measure the relationships and determine effect size of strength, time to peak force generation, fatigability, isometric control, asymmetry, with 6MPT distance. To complete Purpose 2, Pearson correlation analyses were used to evaluate the relationship between maximal HGS and 1) rate of handgrip force development 2) fatigability 3) isometric control, and 4) asymmetry. The strength of the associations was interpreted as: $r<0.10$ is negligible, $r=0.10$-0.39 is weak, $r=0.40$-0.69 is moderate, and $r\geq0.70$ is strong.[27] An alpha level of 0.05 was used for all analyses.

Results

Table 1. Participant Descriptive Statistics.

				n=34
Participant Age (years)				23.76±3.57
Standing Height (centimeters)				173.23±8.28
Weight (kilograms)				76.11±12.62
BMI (kg/m²)				25.09±3.45
Right Hand Dominant (n (%))				29 (85.3)
Left Hand Dominant (n (%))				5 (14.7)
Female (n (%))				20 (58.8)
Weekly MVPA (min)				685.19±655.19*
Six-Minute Push Test Distance (feet)				1112.17±92.84
Maximal Handgrip Strength (kilograms)				41.85±9.65
Handgrip Time to Peak Force Generation (seconds)				0.140±0.037
Handgrip Fatiguability (%)				22.40±10.12
Handgrip Isometric Control (% variation)				2.35±1.20
Handgrip Asymmetry (OR)				1.10±0.08

*n=33, one outlier removed; Moderate to vigorous physical activity (MVPA).

The descriptive statistics of the participants are shown in Table 1. There were weak to near moderate negative associations between strength, time to peak force generation, fatigue, isometric control, and asymmetry and the outcomes of the 6MPT (Purpose 1) shown in Table 2. The association between fatiguability and the 6MPT was the only relationship shown to be significant. Weak associations were found between the additional measures of grip strength assessing muscle function and maximal HGS (Purpose 2), although insignificant. Concurrent validity of the additional measures of grip strength cannot be determined due to the statistical findings. All correlation data for both purposes is shown in Table’s 2 and 3.

Table 2. Results for Correlation of all Measures of Handgrip Strength with 6-Minute Push Test (6MPT)

Outcome Measure	**6MPT**	**95% CI**
Maximal Handgrip Strength	r=-0.14; p=0.42	-0.458 – 0.206
Handgrip Time to Peak Force Generation	r=-0.10; p=0.58	-0.422 – 0.249
Handgrip Fatiguability	r=-0.35; p=0.05*	-0.612 – 0.008
Handgrip Isometric Control	r=-0.19; p=0.27	-0.500 – 0.154
Handgrip Asymmetry	r=0.20; p=0.27	-0.155 – 0.499

* denotes significance

Table 3. Results for Correlation of Additional Measures of Handgrip Strength with Maximal Handgrip Strength

Outcome Measure	Maximal Handgrip Strength	95% CI
Maximal Handgrip Strength	r=1.00	-
Handgrip Time to Peak Force Generation	r=-0.12; p=0.49	-0.442 – 0.226
Handgrip Fatiguability	r=-0.28; p=0.10	-0.568 – 0.060
Handgrip Isometric Control	r=-0.24; p=0.18	-0.531 – 0.112
Handgrip Asymmetry	r=-0.32; p=0.06	-0.597 – 0.015

Discussion

The purpose of this study was to determine the correlations between maximal strength, time to peak force generation, fatigability, isometric control, and asymmetry to a 6MPT test in ambulatory young adults using wheelchairs. Fatiguability and aerobic capacity as measured by the 6MPT were negatively associated, and this association was of weak approaching moderate strength. Although there were no statistically significant correlations between the additional muscle function measures (i.e., time to peak force generation, fatigue, isometric control, and asymmetry) and the 6MPT, there is some evidence suggesting weak association between these measures of muscle function and estimated aerobic capacity estimated by the 6MPT in manual wheelchair users.

The secondary purpose was to evaluate the relationship between the additional grip tasks to maximal HGS. No statistically significant correlations were found when comparing the four additional measures to maximal HGS. However, there is some evidence of weak negative relationships between all additional measures and maximal HGS. When considering these findings, fatiguability may be a useful estimate of aerobic capacity in clinical populations. While clinicians should continue to use gold standard methods such as laboratory procedures utilizing metabolic data, or field tests such as the validated 6MPT when assessing aerobic capacity in manual wheelchair users whenever possible, the findings of this study suggests, fatiguability may have utility. The evidence of the presented relationships showed additional measures of grip strength measured by electronic handgrip dynamometry may be used in conjunction with maximal HGS to assess muscle strength and function.

We found a negative weak association between maximal HGS and the outcome of the 6MPT distance which is used to estimate aerobic capacity. These findings are inconsistent with the hypothesis and previous research. Although there is a lack of evidence existing that shows the relationship between measures of handgrip measured with electronic handgrip dynamometry on aerobic capacity, there are proposed mechanisms as to why HGS and aerobic exercise may be linked. Aerobic exercise induces mitochondrial adaptations and elicits changes in different growth factor levels in skeletal muscle tissue leading to positive protein turnover balance and improves muscular strength and hypertrophy.[28] The mechanisms of strength adaptations from aerobic activity can be supported from the findings in a study by Crane et al., wherein it was found that the active participants had higher relative HGS compared to those in the sedentary group.[29] These findings were thought to be derived from greater upper limb habitual activity similarly seen in high mechanical loads on the upper extremity during wheelchair propulsion.[30] Similarly to Crane et al.'s findings, a study aiming to evaluate the effects of maximum aerobic capacity and ratings of perceived exertion on muscular strength via handgrip and endurance in 83 male students and office workers, a strong significant relationship between HGS and VO_2 max was observed, as well as a weak, approaching moderate relationship between HGS endurance and VO_2 max.[31]

In parallel to our results that show associations between handgrip time to peak force generation and isometric control with maximal HGS, Klawitter et al. found positive moderate and negative moderate relationships between handgrip rate of force development, and submaximal force control to maximal strength, respectively.[13] The associations found in in this pilot study utilizing the same methods with electronic handgrip dynamometry examining the aspects of muscle function in master's age endurance athletes were stronger than those found in our study, but help to further strengthen the evidence of a relationship between additional measures of HGS to assess muscle strength and function as well as the validity of utilizing electronic handgrip dynamometry.

With the evidence of a relationship between the additional measures of HGS measuring muscle strength and function, this information may have clinical significance in the manual wheelchair population. Previous research has shown there to be shorter time to peak force generation when measuring rate of force production at 100 milliseconds.[32] Rate of force development can be considered as an important factor for the performance of motor tasks and activities of daily living. Rodrìguez-Rosell stated that the rate of force development following the onset of a muscle contraction and evaluated at different time intervals (0-300 ms) can provide insight into the physical conditions of individuals such as the influence of neural and intrinsic contractile properties on rate of force development changes. For example, the early phase of rate of force development (<100 ms) has been shown to be mainly influenced by neural drive and intrinsic muscle properties, whereas the rate of force development after 100 ms may be more related to adaptive mechanisms promoting increases in maximal muscle strength.[33] Knowing that, rate of force development would have been a better assessment of neuromuscular function than time to peak force generation. The assessment of rate of force development may be important for subpopulations that use manual wheelchairs including individuals with MS, which leads to neurodegeneration and loss of motor control.[34] In addition, Uyguar et al. investigated handgrip rate of force development and relaxation scaling factors in 12 individuals with MS and twelve controls to determine if upper extremity motor impairments could be detected. This study found that rate of force development was reduced in those with MS, indicating a reduced ability to produce high handgrip rate of force development over submaximal ranges. A reduced ability to produce high handgrip rate of force development is thought to be due to central neuromuscular systems rather than peripheral, which include muscle fiber type.[35] These findings suggest that we can now possibly use handgrip rate of force develop to assess the disease progression in those with MS.

Although not statistically significant, we found there was evidence supporting a weak association between handgrip asymmetry and maximal HGS, which is also clinically relevant to wheelchair users. Individuals with handgrip asymmetry alone have been shown to have 9% greater odds for future accumulating morbidities and when asymmetry is also combined with weakness the odds of future accumulating morbidities increases to 46%.[36] Handgrip asymmetry has also been shown to be associated with functional disability in aging Americans. A study utilizing data of over 18,000 Americans aged ≥50 years from 2006-2016 found increased odds for future activity of daily living (ADL) disability to be 11% in individuals with any handgrip asymmetry alone and 81% for both handgrip asymmetry and weakness[18]. Knowing the risk of functional disability is important as impairments to both instrumental and basic activities of daily living are shown to be highly associated with negative health outcomes including premature mortality and chronic morbidity.[37,38] It is especially important to assess manual wheelchair users as individuals in this population report approximately nine ADL or instrumental ADL (IADL) limitations, which impacts their ability to live independently and is higher than that of individuals who use walkers, crutches, or canes.[39]

This study had some limitations with the first being that participants were not manual wheelchair users. Therefore, our findings may not be generalizable to manual wheelchair users as a whole, but we tried to simulate such use. Additionally, a pacing strategy is often required to perform well during the 6MPT and we observed that several participants struggled with maintaining the same pace throughout the test. Also, one wheelchair was used for all participants and may not have been the appropriate size for some of the larger participants which made regulating tire pressure difficult. Another limitation was the assessment of time to peak force generation rather than rate of force development which is a better assessment of neuromuscular function. Finally, sample size was calculated without considering covariates which may have led to statistically insignificant findings.[40]

Future research should utilize individuals who are manual wheelchair users now that there appears to be evidence of an initial relationship between additional measure of HGS and aerobic capacity. The relationships shown between the additional measures of HGS and maximal HGS indicate the need for more research to assess the concurrent validity electronic handgrip dynamometry as a tool to measure muscle function by comparing the additional measures of HGS to each of their respective assessments.

We found that handgrip fatiguability has a negative association of weak, approaching strength with aerobic capacity, as estimated by the 6MPT. Additionally, we found there is evidence of associations between all additional measures of handgrip and maximal handgrip strength. The findings of this thesis study may be useful for informing clinicians to implement electronic handgrip dynamometry measurements to not only assess muscle function in manual wheelchair users, but also aerobic capacity. Handgrip rate of force development and asymmetry are variables that show promise for assessing muscle function and predicting functional limitations in manual wheelchair user's population.

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References

1. Brault MW. *Household Economic Studies*. U.S. Census Bureau; 2012:24. https://www2.census.gov/library/publications/2012/demo/p70-131.pdf

2. Selph SS, Skelly AC, Wasson N, et al. Physical activity and the health of wheelchair users: A systematic review in multiple sclerosis, cerebral palsy, and spinal cord injury. *Arch Phys Med Rehab*. 2021;102(12):2464-2481.e33. https://doi.org/10.1016/j.apmr.2021.10.002

3. Janssen TWJ, Van Oers C a. JM, Van Der Woude LHV, Hollander AP. Physical strain in daily life of wheelchair users with spinal cord injuries. *Med Sci Sports Exerc*. 1994;26(6):661-670. https://doi.org/10.1249/00005768-199406000-00002

4. William D. McAedle, Frank I. Katch, Victor L. Katch. *Exercise Physiology: Nutrition, Energy, and Human Performance*. Lippincott Williams & Wilkins; 2010.

5. A report: the definition and classification of cerebral palsy April 2006. *Dev Med Child Neurol*. 2007;49:8-14. https://doi.org/10.1111/j.1469-8749.2007.tb12610.x

6. Kasper JD, Chan KS, Freedman VA. Measuring physical capacity: An assessment of a composite measure using self-report and performance-based items. *J Aging Health*. 2017;29(2):289-309. https://doi.org/10.1177/0898264316635566

7. Macdonell R, Nagels G, Laplaud DA, et al. Improved patient-reported health impact of multiple sclerosis: The ENABLE study of PR-fampridine. *Mult Scler*. 2016;22(7):944-954. https://doi.org/10.1177/1352458515606809

8. Vinet A, Bernard PL, Poulain M, Varray A, Gallis DL, Micallef JP. Validation of an incremental field test for the direct assessment of peak oxygen uptake in wheelchair-dependent athletes. *Spinal Cord*. 1996;34(5):288-293. https://doi.org/10.1038/sc.1996.52

9. Goosey-Tolfrey VL, Tolfrey K. The multi-stage fitness test as a predictor of endurance fitness in wheelchair athletes. *J Sports Sci*. 2008;26(5):511-517. https://doi.org/10.1080/02640410701624531

10. Cowan RE, Callahan MK, Nash MS. The 6-min push test is reliable and predicts low fitness in spinal cord injury. *Med Sci Sports Exerc*. 2012;44(10):1993-2000. https://doi.org/10.1249/MSS.0b013e31825cb3b6

11. Franklin BA, Swantek K, Grais S, Johnstone K, Gordon S, Timmis G. Field test estimation of maximal oxygen consumption in wheelchair users. *Arch Phys Med Rehab*. 1990;71(8):574-578.

12. Vanlandewijck YC, Daly DJ, Theisen DM. Field test evaluation of aerobic, anaerobic, and wheelchair basketball skill performances. *Int J Sports Med*. 1999;20(08):548-554. https://doi.org/10.1055/s-1999-9465

13. Klawitter L, Mahoney SJ, Dahl L, et al. Evaluating additional aspects of muscle function with a digital handgrip dynamometer and accelerometer for cognitive functioning in older adults: A pilot study. *ADR*. 2020;4(1):495-499. https://doi.org/10.3233/ADR-200225

14. McGrath R, Johnson N, Klawitter L, et al. What are the association patterns between handgrip strength and adverse health conditions? A topical review. *SAGE Open Med*. 2020;8:2050312120910358. https://doi.org/10.1177/2050312120910358

15. Beaudart C, Rolland Y, Cruz-Jentoft AJ, et al. Assessment of muscle function and physical performance in daily clinical practice. *Calcif Tissue Int*. 2019;105(1):1-14. https://doi.org/10.1007/s00223-019-00545-w

16. Mahoney S, Klawitter L, Hackney KJ, et al. Examining additional aspects of muscle function with a digital handgrip dynamometer and accelerometer in older adults: A pilot study. *Geriatrics*. 2020;5(4):86. https://doi.org/10.3390/geriatrics5040086

17. ATS Committee on Proficiency Standards for Clinical Pulmonary Function Laboratories. ATS statement: guidelines for the six-minute walk test. *Am J Respir Crit Care Med*. 2002;166:111-117. https://doi.org/10.1164/ajrccm.166.1.at1102

18. McGrath R, Vincent BM, Jurivich DA, et al. Handgrip strength asymmetry and weakness together are associated with functional disability in aging Americans. *J Gerontol: A Biol. Sci. Med. Sci.* 2021;76(2):291-296. https://doi.org/10.1093/gerona/glaa100

19. U.S. Department of Health and Human Services. Physical Activity Guidelines for Americans, 2nd edition. 2018. https://health.gov/paguidelines/second-edition/pdf/Physical_Activity_Guidelines_2nd_edition.pdf

20. Warburton DE, Jamnik VK, Bredin SS, et al. Executive summary: the 2011 physical activity readiness questionnaire for everyone (PAR-Q+) and the electronic physical activity readiness medical examination (ePARmed-X+). *Health Fit J Can*. 2011;4(2):24-25.

21. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. 2019;12(1):1-8. https://doi.org/10.70252/EYCD6235

22. Wiles J, H. Boyson. Validity and reliability of a new isometric hand dynamometer - RMIT University. Accessed January 26, 2023. https://researchrepository.rmit.edu.au/esploro/outputs/journalArticle/Validity-and-reliability-of-a-new/9921860497601341

23. Park H won, Baek S, Kim HY, Park JG, Kang EK. Reliability and validity of a new method for isometric back extensor strength evaluation using a hand-held dynamometer. *Ann Rehab Med*. 2017;41(5):793. https://doi.org/10.5535/arm.2017.41.5.793

24. Roberts HC, Denison HJ, Martin HJ, et al. A review of the measurement of grip strength in clinical and epidemiological studies: towards a standardised approach. *Age Ageing*. 2011;40(4):423-429. https://doi.org/10.1093/ageing/afr051

25. D'Emanuele S, Maffiuletti NA, Tarperi C, Rainoldi A, Schena F, Boccia G. Rate of Force development as an indicator of neuromuscular fatigue: A scoping review. *Front Hum Neurosci*. 2021;15. https://doi.org/10.3389/fnhum.2021.701916

26. De Dobbeleer L, Beyer I, Njemini R, et al. Force-time characteristics during sustained maximal handgrip effort according to age and clinical condition. *Exp Gerontol*. 2017;98:192-198. https://doi.org/10.1016/j.exger.2017.08.033

27. Schober P, Boer C, Schwarte LA. Correlation coefficients: appropriate use and interpretation. *Anesth Analg*. 2018;126(5):1763-1768. https://doi.org/10.1213/ANE.0000000000002864

28. Seong JY, Ahn HY, Park Y, Shin S, Ha IH. Association between aerobic exercise and handgrip strength in adults: A cross-sectional study based on data from the Korean National Health and Nutrition Examination Survey (2014–2017). *J Nutr Health Aging*. 2020;24(6):619-626. https://doi.org/10.1007/s12603-020-1372-x

29. Crane JD, MacNeil LG, Tarnopolsky MA. Long-term aerobic exercise is associated with greater muscle strength throughout the life span. *J. Gerontol. A Biol. Sci. Med. Sci*. 2013;68(6):631-638. https://doi.org/10.1093/gerona/gls237

30. van der Woude LHV, Veeger HEJ, Dallmeijer AJ, Janssen TWJ, Rozendaal LA. Biomechanics and physiology in active manual wheelchair propulsion1In adapted form, published as Woude et al. [1].1. *Med Eng Phys*. 2001;23(10):713-733. https://doi.org/10.1016/S1350-4533(01)00083-2

31. Ordudari Z, Habibi E. The Effects of Maximum Aerobic Capacity and Ratings of Perceived Exertion on Muscular Strength and Endurance. *Iran. J. Health Saf. Environ*. 2019;6(3):1291-1296.

32. Jensen RL. Rate of force development and time to peak force during plyometric exercises. Published online 2008.

33. Rodríguez-Rosell D, Pareja-Blanco F, Aagaard P, González-Badillo JJ. Physiological and methodological aspects of rate of force development assessment in human skeletal muscle. *Clin Physiol Funct Imaging*. 2018;38(5):743-762. https://doi.org/10.1111/cpf.12495

34. Dobson R, Giovannoni G. Multiple sclerosis – a review. *Eur J Neurol*. 2019;26(1):27-40. https://doi.org/10.1111/ene.13819

35. Uygur M, De Freitas PB, Barone DA. Rate of force development and relaxation scaling factors are highly sensitive to detect upper extremity motor impairments in multiple sclerosis. *J Neurol Sci*. 2020;408:116500. https://doi.org/10.1016/j.jns.2019.116500

36. Klawitter L, Vincent BM, Choi BJ, et al. Handgrip strength asymmetry and weakness are associated with future morbidity accumulation in Americans. *J Strength Cond Res*. 2022;36(1):106-112. https://doi.org/10.1519/JSC.0000000000004166

37. Dunlay SM, Manemann SM, Chamberlain AM, et al. Activities of daily living and outcomes in heart failure. *Circ Heart Fail*. 2015;8(2):261-267. https://doi.org/10.1161/CIRCHEARTFAILURE.114.001542

38. Hennessy S, Kurichi JE, Pan Q, et al. Disability stage is an independent risk factor for mortality in medicare beneficiaries aged 65 years and older. *PM R*. 2015;7(12):1215-1225. https://doi.org/10.1016/j.pmrj.2015.05.014

39. Allen S, Resnik L, Roy J. Promoting independence for wheelchair users: The role of home accommodations. *Gerontologist*. 2006;46(1):115-123. https://doi.org/10.1093/geront/46.1.115

40. Yang S, Berdine G. “Small” sample size. *Southwest Respir Crit Care Chron*. 2023;11(49):52-55. https://doi.org/10.12746/swrccc.v11i49.1251