International Journal of EXERCISE SCIENCE

Original Research

The Relationships Between Upper and Lower Extremity Muscle Strength, Rate of Force Development, and Fatigue in Adults

MATTHEW LANGFORD[*1,2], KYLE J. HACKNEY[‡2], SARAH ANDREW[†1,2], JOSHUA BATESOLE[*1,2], MAREN BERNTSON[*1,2], KENNEDY BLACK[*1,2], TYLER HOANG[*1,2], LUKUS KLAWITTER[‡3], WILLIAM J. KRAEMER[‡4,5], and RYAN MCGRATH[‡1,2,6,7,8]

[1]Healthy Aging North Dakota, North Dakota State University, Fargo, ND, USA; [2]Department of Health, Nutrition, and Exercise Sciences, North Dakota State University, Fargo, ND, USA; [3]School of Health and Human Performance, Northern Michigan University, Marquette, MI, USA; [4]Department of Human Sciences, The Ohio State University, Columbus, OH, USA; [5]Department of Kinesiology, University of Connecticut, Storrs, CT, USA; [6]Department of Geriatrics, University of North Dakota, Grand Forks, ND, USA; [7]Fargo VA Healthcare System, Fargo, ND, USA; [8]Alliance for Research in Exercise, Nutrition and Activity, Allied Health and Human Performance, University of South Australia, Adelaide, South Australia, AUSTRALIA

*Denotes undergraduate student author, †Denotes graduate student author, ‡Denotes professional author

ABSTRACT

International Journal of Exercise Science 17(4): 1155-1166, 2024. Electronic handgrip dynamometry allows for multiple muscle function aspects to be feasibly measured, yet their relationship with lower extremity muscle function is unknown. We sought to determine the relationships between upper and lower extremity mechanical isometric muscle strength, rate of force development (RFD), and endurance by limb dominance in resistance trained adults. The analytic sample included 30 adults aged 32.1 ± 13.5 years. An electronic handgrip dynamometer ascertained upper extremity strength capacity, RFD, and endurance. Lower extremity strength, RFD, and endurance were collected with the isometric feature on an isokinetic knee dynamometer. Limb dominance was self-reported. Pearson correlations were used for the analyses. Each muscle function attribute on the dominant limb of the upper and lower extremities were correlated: $r = 0.76$ ($p < 0.01$) for strength, $r = 0.37$ ($p = 0.04$) for RFD, and $r = -0.48$ ($p < 0.01$) for endurance. Although strength from the non-dominant limbs were correlated ($r = 0.67$; $p < 0.01$), no significant correlations were observed for RFD ($r = 0.20$; $p = 0.29$) and endurance ($r = -0.21$; $p = 0.26$). For adults aged 18–34 years, only upper and lower extremity strength was correlated on the dominant ($r = 0.69$; $p < 0.01$) and non-dominant limbs ($r = 0.75$; $p < 0.01$); however, strength ($r = 0.88$; $p < 0.01$) and endurance ($r = -0.68$; $p = 0.01$) were correlated in adults aged 35–70 years. Upper and lower extremity fatigability was likewise correlated in females ($r = -0.56$; $p = 0.01$). Our findings suggest that electronic handgrip dynamometry derived strength, RFD, and endurance could be a whole-body indicator of these muscle function attributes given their relationships with the lower extremities. These findings underscore the promise of handgrip dynamometry in routine muscle function assessments across different age groups.

KEY WORDS: Athletes, exercise, movement, physical fitness

INTRODUCTION

Muscle function is comprised of several attributes such as strength, rate of force development (RFD), and endurance. These mechanical aspects of muscle function are necessary to understand health and human performance. For example, strength capacity, RFD, and muscle endurance are associated with frailty, mobility, and diabetes, respectively (14, 32, 40). Moreover, strength decreases injury risk in athletes (34), RFD is linked to jumping distance and fall prevention (2, 23), and muscle endurance is associated with aerobic capacity and walking energetics (29). Given that specific characteristics of muscle function are uniquely associated with health and human performance, it is important to appropriately measure these aspects for their assessment.

Although evaluating muscle function is central for health and human performance, measuring individual aspects of muscle function can pose challenges. Specifically, measuring strength, RFD, and fatigability could be limited by access to equipment, the functional abilities of persons undergoing testing, and risk of injury while examinations are in process (22). Such limitations may reduce the safety and inclusiveness for performing muscle function examinations. Multiple assessment methods should similarly be considered for certain characteristics such as strength (6). Therefore, new and feasible methods for assessing muscle function should be sought to help circumvent barriers to testing.

Handgrip strength is a convenient and reliable assessment of overall muscle strength that generalizes to muscle function (3). The isometric grip force generated during measures of handgrip strength is related to lower extremity strength, thereby supporting maximal handgrip strength as an overall strength capacity assessment (4, 5). Given that handgrip strength has procedural ease and presents whole body strength capacity utility, handgrip strength measurements have emerged as part of health and human performance examinations (7, 20). Indeed, handgrip strength is feasible and provides insights regarding muscle strength; however, traditional methods and tools (e.g., hydraulic handgrip dynamometers) for evaluating handgrip strength only allow for the collection of maximal strength, thereby overlooking other attributes of muscle function such as RFD and endurance (28). These challenges underscore the necessity for innovative methods that can more comprehensively assess muscle function attributes, including in the context of upper-lower extremity relationships. As such, improvement opportunities exist for expanding handgrip strength measurements to be more inclusive of other muscle function attributes.

Electronic handgrip dynamometers allow for the collection of other characteristics of muscle function beyond maximal strength while maintaining feasibility (16, 19). The electronic capabilities of these sophisticated dynamometers permit the observation of force-time curves in real time, thereby allowing other muscle function characteristics to be evaluated, including RFD and endurance. These capabilities may also serve as an approach for increasing safety and inclusiveness in muscle function testing. Despite known correlations between handgrip strength and general muscle function, the unilateral relationships between electronic handgrip dynamometer and extremity-derived RFD and endurance remain unknown. This investigation sought to determine the relationships between upper and lower extremity isometric strength, RFD, and endurance by limb dominance in resistance-trained adults. We hypothesize that correlations will exist between the upper and lower extremities for these muscle function metrics.

METHODS

Participants

A single-visit cross-sectional design was utilized for the study. We pre-specified the recruitment of at least 30 participants as a recommended statistical power proxy for pilot studies (15, 36). Given we wanted to capture a wide age demographic (e.g., master's athletes), participants were included if they were aged 18–70 years (24), and met muscle strengthening recommendations for at least a year from the Physical Activity Guidelines for Americans (26). Persons were excluded if they had any musculoskeletal injury, health condition, or surgical procedure within the previous 6 months that limited physical performance, were not ready to engage in physical activity as determined by the PAR-Q+, or were unable to grasp a handgrip dynamometer or extend their knee due to pain, arthritis, or a surgical procedure.

Flyers, social media, registries, and word-of-mouth were used for study recruitment. Those interested in our investigation contacted a trained interviewer to complete a pre-consent screening questionnaire to determine study eligibility. Given our study criteria, n = 11 persons were excluded for not meeting muscle-strengthening recommendations, and n = 1 was excluded due to knee arthritis. Additionally, a single participant did not arrive at our laboratory after scheduling a visit, and n = 16 were excluded for invalid testing. This research was carried out fully in accordance to the ethical standards of the *International Journal of Exercise Science* (25). Written informed consent was provided by all participants before engaging in study procedures. The North Dakota State University Institutional Review Board approved all protocols.

Protocol

Participants were asked to complete a self-report demographics questionnaire. Standing height and body mass was collected with a Seca stadiometer (Seca; Chino, CA). Body mass index was calculated as kg/m^2. A Biopac SS25LA electronic handgrip dynamometer (Biopac Systems; Goleta, CA), was used to collect strength, RFD, and fatigability. The electronic dynamometer was integrated with a Biopac Student Lab Basic System Acquisition Unit. Calibration of the handgrip dynamometers occurred before data collection. Guidelines for measuring handgrip strength were used to inform our protocols (28). Before handgrip testing, all participants were asked to sit in a chair with their feet flat on the floor, back against the rest, and arms on the rest their hand a neutral position. Trained interviewers explained, demonstrated, and provided verbal encouragement during all handgrip tasks. Participants were allowed a practice trial before engaging in handgrip testing. The order of the hand tested first was block randomized, and participants completed 3 measures for each handgrip task, alternating between hands, with approximately a minute of rest between measurements (27). To reduce fatigue from performing multiple grip tasks while elevating task familiarity, we ordered each handgrip assessment: 1) strength, 2) rate of force development, and 3) fatigability.

For the maximal strength measurement, participants squeezed the electronic handgrip dynamometer on a single hand with maximal effort, exhaling while squeezing, and then released the dynamometer. The highest recorded handgrip strength in kilograms on each hand was included in the analyses.

RFD is often observed as a time component of maximal force production. Accordingly, to determine the RFD, participants were instructed to squeeze the dynamometer "as fast and hard as possible for about a second" after receiving a verbal que to start. RFD was calculated as peak force (kilograms) normalized to time (seconds), and the highest performing value from this grip task on each hand was included in the analyses (9).

Participants were asked to squeeze the dynamometer with maximal effort on a single hand for as long as possible to measure fatigability. The duration of the grip force task ended when a participant fatigued to 50% of their maximal handgrip strength or if they voluntarily released the dynamometer (8). A corresponding grip force curve was generated, and fatigue was determined from the fatigability index (18): $\left(1-\left(\frac{Real\ Area}{Ideal\ Area}\right)\right)x100\%$. The lowest fatigability index on each hand, which represents greater resistance to fatigue, was included in the analyses.

A Biodex System 4 Pro (Biodex; Shirley, NY) was used to measure lower extremity muscle function. Before lower extremity testing, each participant was securely positioned on the Biodex using standard procedures. The order of leg tested first was block randomized to be compatible with the handgrip tasks, and participants completed the protocol in full before the other leg was tested. After standardizing range of motion to each participant, a leg was stationed at 60° of knee flexion (i.e., 0° is full extension) (30). Before the knee extension tasks, a trained interviewer explained the protocol. The execution of each isometric knee extension task was ordered in alignment with the grip tasks to reduce fatigue and elevate familiarity: 1) strength, 2) RFD, and 3) fatigability. For strength measurements, participants extended at the knee with maximal effort for 5 seconds, exhaling on extension, and then relaxed. A total of three trials were conducted on each leg with 30-seconds of rest period between sets. The highest performing knee extension torque value (N · m) on each leg was included in the analyses.

To measure RFD of the knee extensors (or rate of torque development), interviewers instructed participants to extend their knee "as fast and hard as possible for about a second". RFD was calculated as peak torque (N · m) normalized to time in seconds. Each leg had 3 trials, and the highest-performing RFD from each leg was included in the analyses (9).

Given that the Biodex System 4 Pro does not allow for the observance of a torque-time curve during testing, we conducted a repetition-based protocol for inducing fatigue which was modeled from another investigation (38). Specifically, participants were asked to complete 12 isometric knee extensions successively with maximal effort for 5 consecutive seconds, allowing for 3 seconds of rest between each repetition. We calculated fatigability on each leg with the raw torque data (N · m) as the difference in the mean from the last 3 repetitions from the mean of the first 3 repetitions (38).

Statistical Analysis

All analyses were conducted with SAS 9.4 software (SAS Institute; Cary, NC). The descriptive characteristics of the participants were presented as mean ± standard deviation for continuous variables and frequency (percentage) for categorical variables. Given that our experimental design placed credence in unilateral muscle function assessments, we performed our analyses stratified by limb dominance. Accordingly, we performed Pearson correlations for upper and lower limb strength, RFD, and fatigability for the dominant and non-dominant limbs. As an additional analysis, we also quantified the relationships between upper and lower strength, RFD, and fatiguability for the dominant and non-dominant limbs by age group (18–34 years (i.e., non-master's athletes); 35–70 years (i.e., master's athletes)) and sex. An interpretation of correlation coefficients for medicine was utilized (1). An alpha level of 0.05 was used for all analyses.

RESULTS

The descriptive characteristics of the participants are presented in Table 1. Of the 30 participants, 25 (83.3%) were right hand dominant and 13 (43.3%) were aged 35–70 years. Figure 1 displays the relationships between upper and lower extremity strength, RFD, and fatigability for the dominant limbs. Each aspect of muscle function on the dominant limbs for the upper and lower extremities were fairly-to-moderately correlated: $r = 0.76$ ($p < 0.01$) for strength, $r = 0.37$ ($p = 0.04$) for RFD, and $r = -0.48$ ($p < 0.01$) for fatigability. The correlations between upper and lower extremity strength, RFD, and fatigability from the non-dominant limbs are shown in Figure 2. While strength from the upper and lower non-dominant limbs was moderately correlated ($r = 0.67$; $p < 0.01$), no significant correlations existed for rate of force development ($r = 0.20$; $p = 0.29$) and fatigability ($r = -0.21$; $p = 0.26$).

Table 2 presents the correlations between upper and lower extremity strength, rate of force development, and fatigability by age group. For adults aged 18–34 years, upper and lower extremity strength was moderately correlated on the dominant ($r = 0.69$; $p < 0.01$) and non-dominant limbs ($r = 0.75$; $p < 0.01$). However, for adults aged 35–70 years, moderate-to-strong significant correlations were observed for upper and lower extremity limb strength ($r = 0.88$; $p < 0.01$) and fatigability ($r = -0.68$; $p = 0.01$). The correlations between upper and lower extremity strength, rate of force development, and fatigability by sex are shown in Table 3. Dominant limb fatigability was fairly correlated ($r = -0.56$; $p = 0.01$) in females.

Table 1. Descriptive characteristics of the participants.

	Overall (*n* = 30)
Age (years)	32.1 ± 13.5
Female (*n* (%))	19 (63.3)
Non-Hispanic (*n* (%))	29 (96.7)
Married (*n* (%))	12 (40.0)
Completed Bachelor's Degree or Higher (*n* (%))	15 (50.0)
Right Hand Dominant (*n* (%))	25 (83.3)
Right Leg Dominant (*n* (%))	26 (86.7)
Self-Rated Health (*n* (%))	
Excellent	7 (23.3)
Very Good	18 (60.0)
Good	5 (16.7)
Standing Height (cm)	171.8 ± 9.1
Body Mass (kg)	80.5 ± 17.7
Body Mass Index (kg/m^2)	27.1 ± 3.9
Dominant Handgrip Strength (kg)	32.8 ± 12.6
Dominant Handgrip Rate of Force Development (kg/s)	109.7 ± 45.9
Dominant Handgrip Fatigability‡	30.4 ± 7.5
Non-Dominant Handgrip Strength (kg)	30.9 ± 10.0
Non-Dominant Handgrip Rate of Force Development (kg/s)	96.3 ± 32.2
Non-Dominant Handgrip Fatigability‡	31.4 ± 7.2
Dominant Leg Extension Strength (N · m)	166.6 ± 47.9
Dominant Leg Extension Rate of Force Development (N · m/s)†	601.3 ± 223.8
Dominant Leg Extension Fatigability (N · m)	20.0 ± 12.6
Non-Dominant Leg Extension Strength (N · m)	171.1 ± 44.0
Non-Dominant Leg Extension Rate of Force Development (N · m/s)†	645.2 ± 168.0
Non-Dominant Leg Extension Fatigability (N · m)	16.9 ± 13.7

†Could also be referred to as rate of torque development. ‡Determined from the fatigability index.

Table 2. Correlations between upper and lower extremity strength, rate of force development, and fatigability by age group.

	Aged 18–34 Years (*n* = 17)	Aged 35–70 Years (*n* = 13)
Dominant Limbs		
Strength	$r = 0.69$; $p < 0.01$	$r = 0.88$; $p < 0.01$
Rate of Force Development	$r = 0.32$; $p = 0.20$	$r = 0.50$; $p = 0.08$
Fatigability	$r = -0.23$; $p = 0.36$	$r = -0.68$; $p = 0.01$
Non-Dominant Limbs		
Strength	$r = 0.75$; $p < 0.01$	$r = 0.54$; $p = 0.05$
Rate of Force Development	$r = 0.22$; $p = 0.37$	$r = 0.18$; $p = 0.55$
Fatigability	$r = -0.41$; $p = 0.09$	$r = 0.08$; $p = 0.79$

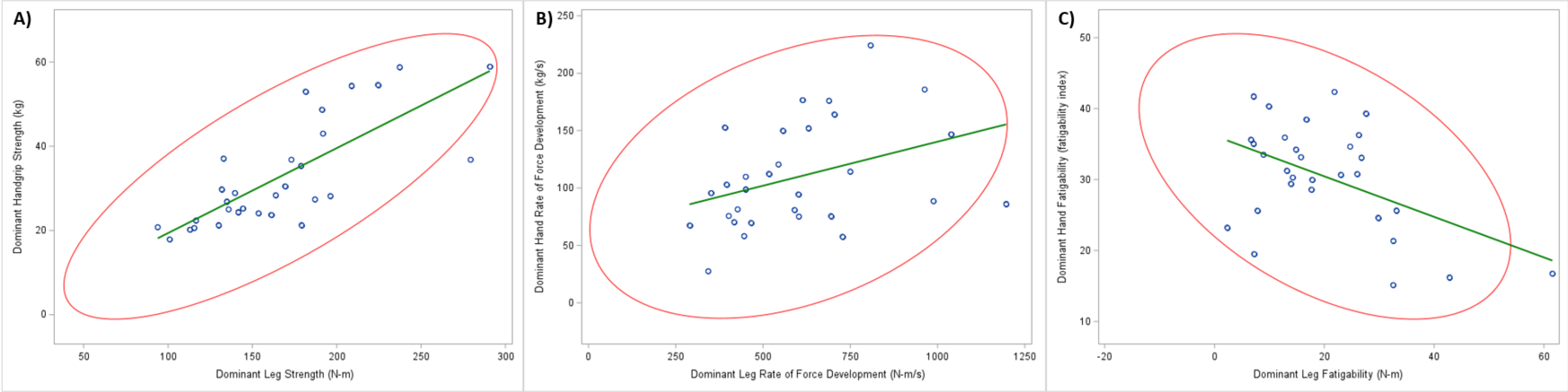

Figure 1. Relationships between upper and lower extremity strength, rate of force development, and fatigability for dominant limbs. A = strength; B = rate of force development; C = fatigability. Green = fitted regression line; Red = 95% confidence ellipse.

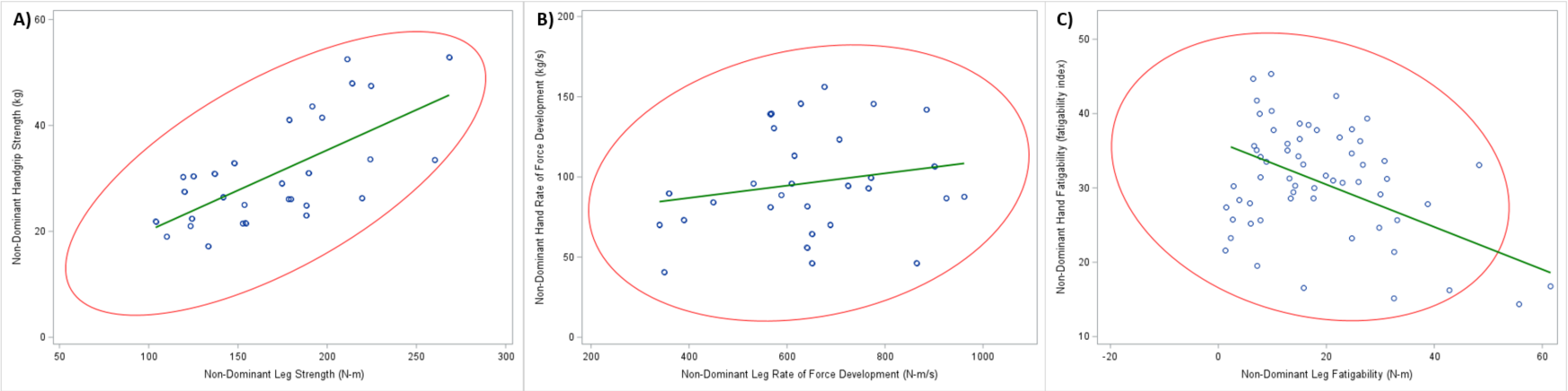

Figure 2. Relationships Between upper and lower extremity strength, rate of force development, and fatigability for the non-dominant limbs. A = strength; B = rate of force development; C = fatigability. Green = fitted regression line; Red = 95% confidence ellipse.

Table 3. Correlations between upper and lower extremity strength, rate of force development, and fatigability by sex.

	Female (n = 19)	Male (n = 11)
Dominant Limbs		
Strength	r = 0.40; p = 0.08	r = 0.47; p = 0.14
Rate of Force Development	r = 0.15; p = 0.52	r = 0.22; p = 0.50
Fatigability	r = −0.56; p = 0.01	r = −0.38; p = 0.24
Non-Dominant Limbs		
Strength	r = 0.32; p = 0.17	r = 0.57; p = 0.06
Rate of Force Development	r = 0.34; p = 0.14	r = −0.10; p = 0.76
Fatigability	r = 0.12; p = 0.60	r = −0.38; p = 0.23

DISCUSSION

The principal findings of this pilot investigation found that electronic handgrip dynamometer-derived strength, RFD, and fatigability were related to lower extremity strength, RFD, and fatigability in resistance-trained adults. Specifically, strength, RFD, and fatigability were fairly-to-moderately correlated between the upper and lower extremities on the dominant limbs, but only a significant correlation was observed for non-dominant upper and lower extremity strength. Similar patterns were observed when considering the age group, such that strength was correlated between the upper and lower extremities, but the magnitude of the correlation elevated in persons aged 35–70 years. Moreover, fatigability was correlated between the upper and lower extremities for those aged 35–70 years, but not in persons aged 18–34 years. Our findings suggest that electronic handgrip dynamometry has promise to serve as a whole-body indicator of strength, RFD, and fatigability.

Limb dominance may factor into performance in unilateral muscle function assessments such as those performed in our investigation. For example, muscle function and coordination tend to be better in dominant extremities relative to non-dominant (12). As such, the role of coordination on the dominant extremities may explain why we observed significant correlations for strength, RFD, and endurance. A large proportion of the population is right hand dominant, but this proportion is dissimilar for the lower extremities (21). Changes in limb dominance may occur depending on injuries or overuse. Voletta et al. (36) found that limb dominance changed depending on the task, wherein tasks that are manipulative the right limbs are preferred, but when involve stability, the left limbs might be favored.

Our findings align with previous studies that have found a relationship between upper and lower extremity strength as measured by dynamometry (4, 5, 34). Sports medicine practitioners should carefully select strength and conditioning tests for examining human performance (22). For example, while algorithmic flowcharts help to guide test selection, athlete abilities should also warrant attention (11, 38). Limb dominance and age may factor into the findings, but we advise caution in defining dominance as it is largely task dependent. Handgrip protocols as a non-invasive tool for assessing strength, RFD, and fatigue could be useful in older populations with a specific metabolic demand. Given the novelty of electronic handgrip dynamometry in assessing several measures of muscle function for human performance, more research is needed to specify measurement utility and response to intervention.

While limb dominance may have factored into our findings, age and sex may have also been influential. For example, males exhibit steeper muscle function decline relative to females, especially in the lower extremities (10). Muscle strength and mass likewise decrease with age, which may help to elucidate our observed correlations for strength and fatigability in master's athletes in the dominant limbs (32). Sex-based differences in our findings could be underpinned by endocrine and muscle fiber type, as females have a greater prevalence of slower-twitch fibers, which enables slower oxidative fibers and higher oxidative capacity for elevated endurance and recovery (13). Such findings support the need to examine sex as a biological variable for human performance research (17).

Some limitations should be noted. We included a sample of resistance trained athletes, limiting our findings' generalizability. Other protocols for ascertaining lower extremity fatigability, such as a sustained isometric contraction, may have altered our correlations, but tools to measure were not available. Similarly, other knee angles while seated during testing may have changed lower extremity muscle function performance. We chose to evaluate strength before RFD to elevate familiarization of the novel handgrip testing and to reduce spuriousness in RFD measurements such that participants knew the differences in contraction speed. Future research may examine the role of electronic handgrip dynamometer derived strength, RFD, and fatigability on the lower extremities in community-dwelling older adults for helping to expand the usage of electronic handgrip dynamometry into clinical settings.

Our findings showed that upper extremity strength, RFD, and endurance, as measured with electronic handgrip dynamometry, were related to the same metrics in the lower extremities in resistance-trained adults. Limb dominance and age may also factor into the findings. These results suggest that electronic handgrip dynamometry may serve as a whole-body indicator of muscle strength, RFD, and endurance. Electronic handgrip dynamometry could be especially useful for muscle function testing when considering low injury risk, accelerated time to recovery, and inclusiveness in abilities for a possible wide range of athletes.

ACKNOWLEDGEMENTS

The Healthy Aging Brain and Body Registry at North Dakota State University was used for this investigation to recruit study participants. Research reported in this publication was supported in part by the National Institute on Aging of the National Institutes of Health under Award Number R15AG072348 (to RM) as a student-led pilot project. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

REFERENCES

1. Akoglu H. User's guide to correlation coefficients. Turk J Emerg Med 18(3): 91-93, 2018.

2. Bellumori M, Jaric S, Knight CA. Age-related decline in the rate of force development scaling factor. Motor Control 17(4): 370-381, 2013.

3. Bhasin S, Travison TG, Manini TM, Patel S, Pencina KM, Fielding RA, Magaziner JM, Newman AB, Kiel DP, Cooper C, Guralnik JM. Sarcopenia definition: The position statements of the sarcopenia definition and outcomes consortium. J Am Geriatr Soc 68(7): 1410-1418, 2020.

4. Bohannon RW. Are hand-grip and knee extension strength reflective of a common construct? Percept Mot Skills 114(2): 514-518, 2012.

5. Bohannon RW, Magasi SR, Bubela DJ, Wang Y-C, Gershon RC. Grip and knee extension muscle strength reflect a common construct among adults: Grip and knee strength. Muscle Nerve 46(4): 555-558, 2012.

6. Buckner SL, Jessee MB, Mattocks KT, Mouser JG, Counts BR, Dankel SJ, Loenneke JP. Determining strength: A case for multiple methods of measurement. Sports Med 47: 193-195, 2017.

7. Cronin J, Lawton T, Harris N, Kilding A, McMaster DT. A brief review of handgrip strength and sport performance. J Strength Cond Res 31(11): 3187-3217, 2017.

8. De Dobbeleer L, Beyer I, Njemini R, Pleck S, Zonnekein N, Mets T, Bautmans I. Force-time characteristics during sustained maximal handgrip effort according to age and clinical condition. Exp Gerontol 98: 192-198, 2017.

9. 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 15: 701916, 2021.

10. Ditroilo M, Forte R, Benelli P, Gambarara D, De Vito G. Effects of age and limb dominance on upper and lower limb muscle function in healthy males and females aged 40–80 years. J Sports Sci 28(6): 667-677, 2010.

11. Fares MY, Khachfe HH, Salhab HA, Bdeir A, Fares J, Baydoun H. Physical testing in sports rehabilitation: Implications on a potential return to sport. Arthrosc Sports Med Rehabil 4(1): e189-198, 2022.

12. Fort-Vanmeerhaeghe A, Milà-Villarroel R, Pujol-Marzo M, Arboix-Alió J, Bishop C. Higher vertical jumping asymmetries and lower physical performance are indicators of increased injury incidence in youth team-sport athletes. J Strength Cond Res 36(8): 2204-2211, 2022.

13. Haizlip K, Harrison B, Leinwand L. Sex-based differences in skeletal muscle kinetics and fiber-type composition. Physiology 30(1): 30-39, 2015.

14. Hester GM, Ha PL, Dalton BE, VanDusseldorp TA, Olmos AA, Stratton MT, Bailly AR, Vroman TM. Rate of force development as a predictor of mobility in community-dwelling older adults. J Geriatr Phys Ther 44(2): 74-81, 2021.

15. Julious SA. Sample size of 12 per group rule of thumb for a pilot study. Pharm Stat 4(4): 287-291, 2005.

16. Klawitter LA, Hackney KJ, Christensen BK, Hamm JM, Hanson M, McGrath R. Using electronic handgrip dynamometry and accelerometry to examine multiple aspects of handgrip function in master endurance athletes: A pilot study. J Strength Cond Res 37(9): 1777-1782, 2023.

17. Landen S, Hiam D, Voisin S, Jacques M, Lamon S, Eynon N. Physiological and molecular sex differences in human skeletal muscle in response to exercise training. J Physiol 601(3): 419-434, 2023.

18. Lou J-S. Techniques in assessing fatigue in neuromuscular diseases. Phys Med Rehabil Clin N Am 23(1): 11-22, 2012.

19. McGrath R, Tomkinson GR, Clark BC, Cawthon PM, Cesari M, Al Snih S, Jurivich DA, Hackney KJ. Assessing additional characteristics of muscle function with digital handgrip dynamometry and accelerometry: Framework for a novel handgrip strength protocol. J Am Med Dir Assoc 22(11): 2313-2318, 2021.

20. McGrath RP, Kraemer WJ, Snih SA, Peterson MD. Handgrip strength and health in aging adults. Sports Med 48(9): 1993-2000, 2018.

21. McGrath TM, Waddington G, Scarvell JM, Ball NB, Creer R, Woods K, Smith D. The effect of limb dominance on lower limb functional performance – A systematic review. J Sports Sci 34(4): 289-302, 2016.

22. McGuigan MR, Cormack SJ, Gill ND. Strength and power profiling of athletes: Selecting tests and how to use the information for program design. Strength Cond J 35(6): 7-14, 2013.

23. McLellan CP, Lovell DI, Gass GC. The role of rate of force development on vertical jump performance. J Strength Cond Res 25(2): 379-385, 2011.

24. Moorman AJ, Dean LS, Yang E, Drezner JA. Cardiovascular risk assessment in the older athlete. Sports Health Multidiscip Approach 13(6): 622-629, 2021.

25. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1, 2019.

26. Piercy KL, Troiano RP, Ballard RM, Carlson SA, Fulton JE, Galuska DA, George SM, Olson RD. The physical activity guidelines for americans. JAMA 320(19): 2020-2028, 2018.

27. Reijnierse EM, De Jong N, Trappenburg MC, Blauw GJ, Butler-Browne G, Gapeyeva H, Hogrel JY, McPhee JS, Narici MV, Sipilä S, Stenroth L. Assessment of maximal handgrip strength: How many attempts are needed? J Cachexia Sarcopenia Muscle 8(3): 466-474, 2017.

28. Roberts HC, Denison HJ, Martin HJ, Patel HP, Syddall H, Cooper C, et al. A review of the measurement of grip strength in clinical and epidemiological studies: Towards a standardised approach. Age Ageing 40(4): 423-429, 2011.

29. Roshanravan B, Patel KV, Fried LF, Robinson-Cohen C, De Boer IH, Harris T, Murphy RA, Satterfield S, Goodpaster BH, Shlipak M, Newman AB. Association of muscle endurance, fatigability, and strength with functional limitation and mortality in the health aging and body composition study. J Gerontol A Biol Sci Med Sci 72(2): 284-291, 2017.

30. Šarabon N, Kozinc Ž, Perman M. Establishing reference values for isometric knee extension and flexion strength. Front Physiol 12: 767941, 2021.

31. Sawada SS, Lee I-M, Naito H, Tsukamoto K, Muto T, Blair SN. Muscular and performance fitness and the incidence of type 2 diabetes: Prospective study of Japanese men. J Phys Act Health 7(5): 627-632, 2010.

32. Siparsky PN, Kirkendall DT, Garrett Jr WE. Muscle changes in aging: Understanding sarcopenia. Sports Health 6(1): 36-40, 2014.

33. Strandkvist V, Larsson A, Pauelsen M, Nyberg L, Vikman I, Lindberg A, Gustafsson T, Röijezon U. Hand grip strength is strongly associated with lower limb strength but only weakly with postural control in community-dwelling older adults. Arch Gerontol Geriatr 94: 104345, 2021.

34. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. Sports Med 46(10): 1419-1449, 2016.

35. VanVoorhis CW, Morgan BL. Understanding power and rules of thumb for determining sample sizes. Tutor Quant Methods Psychol 3(2): 43-50, 2007.

36. Velotta J, Weyer J, Ramirez A, Winstead J, Bahamonde R. Relationship between leg dominance tests and type of task. Presented at ISBS-Conference Proceedings Archive. Int Soc Biomech Sports, 2011.

37. Weakley J, Black G, McLaren S, Scantlebury S, Suchomel TJ, McMahon E, Watts D, Read DB. Testing and profiling athletes: Recommendations for test selection, implementation, and maximizing information. Strength Cond J 46(2): 159-179, 2023.

38. White C, Dixon K, Samuel D, Stokes M. Handgrip and quadriceps muscle endurance testing in young adults. SpringerPlus 2(1): 451, 2013.

39. Xue Q-L. The frailty syndrome: Definition and natural history. Clin Geriatr Med 27(1): 1-15, 2011.