Ann Appl Sport Sci, 12(03): e1399, 2024.
http://www.aassjournal.com; e-ISSN: 2322–4479; p-ISSN: 2476–4981. 10.61186/aassjournal.1399

ORIGINAL ARTICLE

Comparison of the Dynamometer- and Kinematics-based Analyses for Measuring Individual Quadriceps Muscle Torque: A Pilot Study

[1]Christopher L. Rawdon*, [2]Christopher P. Ingalls, [2]Feng Yang, [2]Jeff S. Otis, [3]Kyle Brandenberger, [2]Mekensie Jackson

[1]Department of Exercise Science, Kinesiology Faculty, Mercer University: 1501 Mercer University Drive Macon, GA, US, 31207. [2]Department of Kinesiology and Health, Exercise Science, Georgia State University: 125 Decatur Street Atlanta, GA, US, 30303. [3]Department of Respiratory Therapy, Georgia State University: PO Box 4019 Atlanta, GA, US, 30303.

Submitted April 22, 2024; Accepted in final form June 25, 2024.

ABSTRACT

Background. Current studies on exercise-induced injury effects lack direct force measurements of individual agonist muscles post-injury, relying on indirect markers. Transcutaneous muscle stimulation assesses the intrinsic force-producing capacity of the entire muscle group but has not been used to compare individual muscle strength. **Objectives.** Compare the reliability of dynamometer-based and kinematic-based methods in measuring the torque produced by electrical stimulation of individual quadriceps muscles. **Methods.** Eight males (30.3±3.9 years) were enrolled for a two-day test-retest study. On Day 1, peak isometric torque during maximal voluntary contractions (MVC) was assessed, followed by peak isometric tetanic torque produced by electrical stimulation (20 & 80 Hz) of the vastus medialis, rectus femoris, and vastus lateralis muscles using the Biodex dynamometer with the knee at 90° and the shin pad 2 cm above the lateral malleolus. Subjects performed two MVCs for four seconds each. Isometric torque during 20 and 80 Hz stimulations of the individual quadriceps muscles was then recorded by the dynamometer. The kinematics of the weighted leg during 20 and 80 Hz electrical stimulation-induced concentric contractions targeting the individual muscles were collected by a motion capture system (Vicon) to calculate peak torque. Procedures were repeated within seven days. Test-retest reliability was analyzed using intraclass correlation coefficients (ICC) and Bland-Altman plots. **Results.** Both methods showed strong test-retest reliability (Biodex ICC=0.95 [95% CI: 0.90-0.97]; Vicon ICC=0.98 [95% CI: 0.96-0.98]). The reliability of both methods was further supported by the Bland-Altman plot. **Conclusion.** Dynamometer- and kinematics-based analyses were reliable for measuring individual quadricep muscle torque produced by transcutaneous electrical stimulation.

KEYWORDS: ***Transcutaneous Neuromuscular Electrical Stimulation, Muscle Strength, Muscle Contraction, Isometric Contraction, Muscle Skeletal.***

INTRODUCTION

Research investigating exercise-induced injury in humans typically assesses skeletal muscle strength and soreness in a muscle group acting on a given joint and/or via blood markers of muscle injury. Notedly, exercise-induced muscle injury causes an immediate 25-50% reduction of maximal strength in injured skeletal muscle groups, requiring days to weeks to recover

*. Corresponding Author:
Christopher L Rawdon, Ph.D.
E-mail: rawdon_cl@mercer.edu

fully (1, 2). Eccentric contractions are known to injure and reduce the strength of the quadriceps muscles group (i.e., knee extensors), but whether the vastus medialis (VM), vastus lateralis (VL), vastus intermedius (VI), and rectus femoris (RF) are injured to the same extent is unclear. Differences in muscle architecture (e.g., pennation angle, fascicle, and muscle length), previous usage, and recruitment patterns among agonist muscles may disproportionately injure muscles of the quadriceps. The notion of exercise-induced differential injury of agonist muscles is supported by nonuniform changes in indirect markers of muscle injury (e.g., magnetic resonance imaging [MRI] and tensiomyography) amongst the individual muscles (3-6). However, there are no published studies of strength deficits between individual agonist muscles following exercise-induced injury.

Electrical stimulation (i.e., pulse duration of <1ms) of skeletal muscle via electrodes placed on the skin is known to cause force production from the induction of action potentials on motor neuron axons or intramuscular terminal motor axon branches (7). Previous studies in humans have only investigated the muscle group's stimulated force generation effects to evaluate the degree of exercise-induced injury (8-12). The ability to quantify individual muscle torques at various stimulation frequencies would allow the comparison of torque deficits across agonist muscles. Presently, no research protocols measure the intrinsic force capacity of individual skeletal muscle in humans before and after skeletal muscle injury. Current knowledge on differential injury among agonist muscles has been based on measurements including MRI, tensiomyography, and EMG, which are not direct force measurements, and each of them has shortcomings when interpreting the presence of functional muscle injury.

To understand the degree of exercise-induced differential strength loss amongst agonist muscles, we first sought to determine the reliability and sensitivity of two methods of assessing muscle torque from the individual quadriceps muscles: 1) dynamometer-based and 2) kinematics-based analyses. Although we have used the dynamometer (i.e., Biodex) to assess the muscle torque of the entire quadriceps group, the sensitivity of the Biodex to measure the stimulated torque of individual injured and weak quadriceps muscles may be at the limit of the system to yield valid and reliable data. It has been shown that low-frequency (20 Hz) induced torque of the knee extensor group can decline to up to 60% immediately following eccentric contractions (8, 11). If any of the injured quadriceps muscles have a similar loss in torque, it is critical to determine whether or not the Biodex dynamometer is sensitive enough to pick up the torque produced by the separate muscles at a lower stimulation frequency. Kinematic-based analyses can also be used to calculate the torque produced from direct stimulation of an individual muscle by measuring limb acceleration. However, the accuracy and reproducibility of the motion-based modality to measure individual muscle force have also not been evaluated. Therefore, this study aimed to compare dynamometer-based and kinematics-based methods of measuring individual quadriceps muscle torque during submaximal tetanic contractions induced by electrical stimulation.

MATERIALS AND METHODS

Experimental Design. This study was approved by the Georgia State University Institutional Review Board (IRB Number: H20435), and all experimental procedures conformed with the Declaration of Helsinki. After providing informed consent and confirming eligibility, subjects warmed up on the treadmill at a self-chosen walking pace for five minutes. All strength assessments were conducted on the subject's left leg. The left leg was chosen because the position of stationary cameras in our lab produced higher reliability in picking up the reflective markers on the left side. After the warm-up, the subjects performed two isometric maximal voluntary contractions (MVCs) on the Biodex with the knee at 90°. Peak isometric torque produced by three directly stimulated muscle tetanic contractions to each muscle at a low frequency (20 Hz) and two at a high frequency (80 Hz) were recorded by the Biodex dynamometer. Following this, the subject's leg was removed from the Biodex, and an ankle weight corresponding to 5% of their body mass was wrapped around their ankle. The subject then underwent three directly stimulated muscle tetanic concentric contractions at a low frequency and two at a high frequency for each muscle. The Vicon motion capture system recorded the resulting knee extension using 5 reflected markers on the left leg. After these recordings, the subject was scheduled for the second data collection session within seven days following the first meeting. On the second day of data collection, the subjects repeated the protocol of a walking warm-up, two isometric MVCs on the Biodex, stimulated isometric torque on the Biodex, and stimulated concentric torque with an ankle weight recorded by the Vicon motion capture system. The accuracy and consistency of the kinematics-based approach for measuring individual muscle torques were compared to the individual muscle torques measured via the Biodex from both time points.

Subjects. Nine male sedentary subjects were recruited for the study, 18 to 35 years of age. Eight subjects completed the protocol, with one dropping out, citing pain from stimulation. Sedentary is operationally defined as spending most of the day in activities requiring minimal energy expenditure or sitting/lying and failing to achieve the American College of Sports Medicine's (ACSM) recommended weekly amount of physical activity (i.e., at least 75-150 minutes per week of moderate-to-vigorous exercise). Exclusion criteria included recreationally active subjects who participated in activities with repeated plyometric or jumping motions or participated in resistance training of the lower body up to once a week, subjects who were required to have medical clearance for exercise after completing the ACSM exercise preparticipation screening, and those with traumatic left knee injuries (e.g., ligament tear, tendinopathy). The formula $N=[(Z\alpha+Z\beta)/C]^2+3$ was used to estimate sample size for a correlation study with $Z\alpha$ & $Z\beta$ representing the standard normal deviation for alpha and beta respectively, and $C=0.5*\ln[(1+r)/(1-r)]$. Seven subjects were needed to correlate 0.90 with a power of 0.80 and α (two-tailed) of 0.05.

Maximal Voluntary Contraction Torque Assessment. MVC strength of the quadriceps muscles was evaluated using the Biodex dynamometer. Subjects performed two MVCs with the knee at 90°. Maximal voluntary torque is the mean of the greatest torque values achieved from the two contractions. Participants were strapped into the Biodex using a seatbelt, shoulder harness, and thigh harnesses and contracted their quadriceps muscles with their shin against the padded bar (2 cm above lateral malleolus) of the Biodex dynamometer. One minute of recovery was given after the first contraction.

Direct Electrical Stimulation of Quadriceps Muscle. Electrically induced torque produced by three superficial knee extensor muscles (VL, VM, RF) on the left leg was evaluated using kinematic/kinetic analysis and a Biodex dynamometer. Directly stimulated muscle tetanus is widely used to determine changes in muscle activation and force development after various types of injury and fatigue in humans (8, 9, 11, 12). Figure 1 displays photographs of the subject set-up before stimulated isometric contractions. Pairs of 5 x 5 cm stimulating electrodes (U Ultimate; Cheyenne, WY) were placed 3 cm apart over one of the quadriceps muscles at a time. The left thigh was shaved, and the skin where the electrodes were placed was wiped with sandpaper and alcohol swabs to increase conductance. The placement of the electrodes was based on anatomical insertions for the three muscles, visual inspection, and previous research investigating transcutaneous electrical nerve stimulation and motor points for the individual quadriceps muscles (13-16). The cathode electrode for the VM was applied to joint space proximal to the anterior border of the medial collateral ligament, with the anode electrode placed 3 cm in-line with the muscle origin (i.e., intertrochanteric line). For the RF, the cathode electrode was placed approximately two-thirds the distance between the superior border of the patella and the anterior superior iliac spine, with the anode electrode placed 3 cm away in-line with the origin (i.e., anterior inferior iliac spine). The cathode electrode for the VL was placed approximately two-thirds the distance between the lateral epicondyle and greater trochanter, with the anode electrode 3 cm towards the origin (i.e., greater trochanter). Muscles were stimulated by the voltage and current settings of a Digitimer (model DS7AH) electrical stimulator. At the same time, the stimulation frequency (20 Hz and 80 Hz) and duration (0.4 s) were set by the "Sync Train" output of a Grass S48 electrical stimulator that was connected to the trigger input of the Digitimer stimulator. 20 and 80 Hz are stimulation frequencies previously reported in protocols investigating intrinsic force capabilities of the knee extensor group (8, 9, 11, 12, 17). Permanent markers were used to identify the location of stimulating electrodes for multi-day analyses, and photos and measurements were taken for reference. Subjects were seated and strapped to the Biodex chair and asked to relax between contractions to relieve muscle tension completely. The output current and voltage from the Digitimer were set to 200 mA and 200 mV, respectively. After the first series of three low-frequency tetanic contractions at 20 Hz, each muscle was then stimulated at a frequency of 80 Hz for two stimulations. Following the last contraction at the high frequency, the wires connected to the stimulator were placed on the stimulating electrodes for the next muscle. All stimulations were separated by 60 seconds of rest.

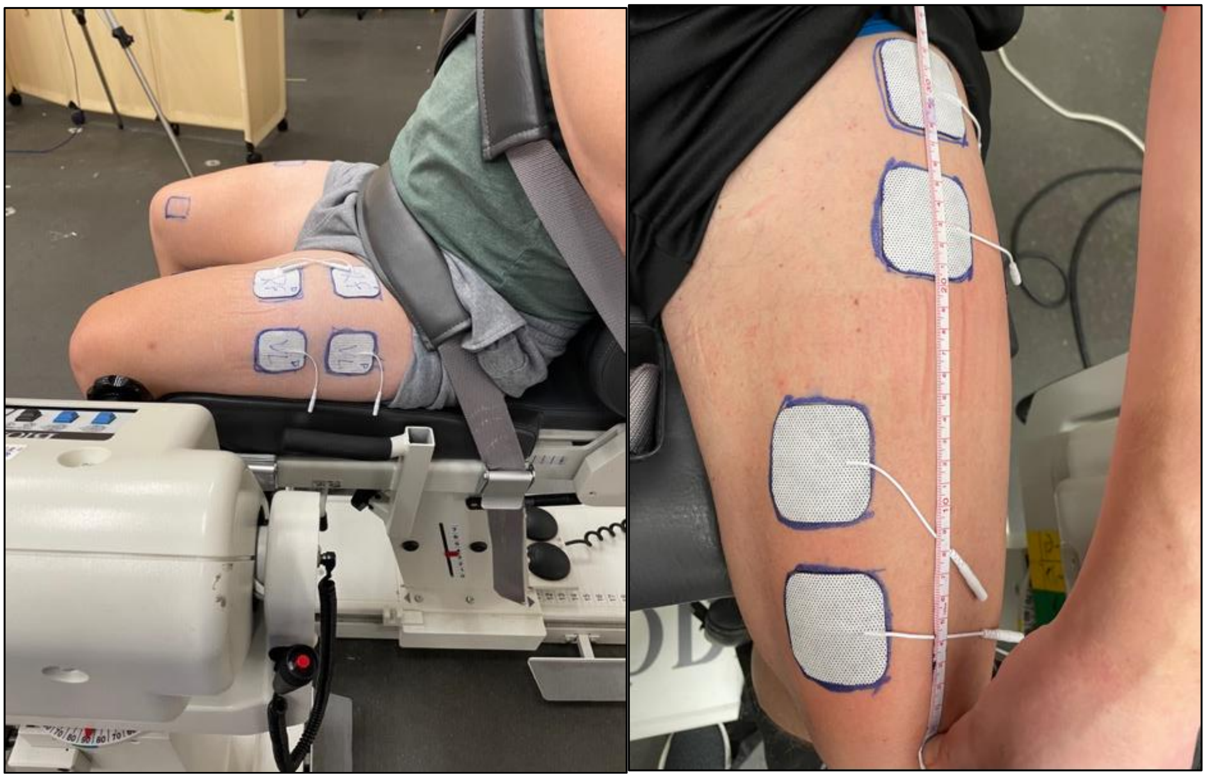

Figure 1. Photographs of electrode placement during set-up for stimulated individual quadriceps muscle isometric contractions on the Biodex dynamometer. Additionally, a thigh harness (not depicted) was used to keep the thigh stationary during stimulations.

Kinematic-Kinetic Assessment of Individual Muscle Torques. Kinematic analysis was used to calculate torque produced by VL, VM, and RF during individual tetanic contractions (see procedure above). During knee extensor measurements, the subject's thigh, chest, and waist were strapped down in the Biodex chair. An ankle weight that was 5% of the subject's recorded body weight was placed around the subject's ankle, and an ankle brace was applied to prevent ankle movement during contractions. The placement of the subject on the seat was recorded to standardize the within-subject measurements between trials. During the assessment, each muscle (VM, VL, RF) underwent three tetanic contractions at 20 Hz and two at 80 Hz. The limb's movement resulting from each contraction was recorded by Vicon cameras and then processed by Vicon Nexus software version 2.7 (OMG, Oxford, England). All contractions were separated by 60 seconds of rest. Reflective markers were placed on the thigh, knee, shank, ankle, and foot to measure the leg movement from a relaxed resting position to the end of each contraction. The knee joint angle was determined by inverse kinematics using the filtered markers' paths. Peak concentric torque (T) was calculated as $T=I\alpha+Twt$, where I is the leg-foot-weight segment's moment of inertia about the knee joint, α is the angular acceleration of the knee joint, which was derived as the second-order differentiation of the knee joint angle, and Twt is torque induced by segment's gravity concerning the knee joint. I and the segment's weight were obtained using the anthropometric model (18). Customer Matlab subroutines were used to calculate knee torque.

Data Analysis and Statistics. Test-retest data was analyzed using the intraclass correlation coefficient (ICC), Cronbach's alpha, and Altman-Bland analysis. ICC serves as a measure of repeatability that evaluates both the degree of correlation and agreement between measurements (19). ICC values below 0.5 have poor reliability, between 0.5 and 0.75 is considered moderate reliability, 0.75 and 0.9 is considered good reliability, and greater than 0.90 is considered excellent reliability based on a 95% confidence interval (19). A two-way mixed-effects model was chosen to calculate ICC values. We fail to reject the null hypothesis of normal distribution for all conditions given that Shaprio-Wilks testing for normality produced non-significant p-values ($p \geq 0.085$). Altman-Bland analysis is a graphic interpretation of agreement that uses the difference of means between measurements and the limits of agreement, which is "defined as the range expected to include 95% of the future differences between two methods" (20). Cronbach's alpha measures the internal consistency for repeated assessments (21). Pearson correlations also assessed the agreement between the first and second sessions for the torque measurements recorded by the Biodex and Vicon motion capture. Pearson's correlation was used to determine the degree of association between the torque measurements recorded on the Biodex and Vicon. A mixed-design ANOVA with repeated measures on time and method was used to evaluate changes in torque over time across the muscles and methods. A paired t-test was used to compare maximal voluntary contraction torque between the first and second sessions. All statistical analysis was performed using SPSS version 28 (IBM: Armonk, NY). Values in the results will be reported as means±SD. Statistical significance is set at an α-level of 0.05.

RESULTS

Subjects. Eight subjects completed the research protocol, with one additional subject dropping out due to pain during the stimulation. The average age of the subjects was 30.3±3.9 years. The average BMI of the subjects was 31.0±5.0 kg/m^2. There was no significant difference in the isometric MVC torque between sessions ($p=0.297$, Day 1 =307.7±34.0 N●m, Day 2 =291.8±28.3 N●m). One subject's kinematic data could not be processed for analysis, so direct comparisons between Vicon and Biodex were not performed for this subject.

Reliability Analysis. A summary of torque produced by the knee extensor muscles at low and high-frequency stimulation across both days is displayed in Table 1. Figure 2 illustrates the distribution of high-frequency (80 Hz) stimulated torque for individual quadriceps muscles, with panel A showing the box plot for isometric conditions and panel B depicting the box plot for concentric conditions across the VM, RF, and VL. Table 2 shows the ICC, Cronbach's alpha, and Bland-Altman for the Biodex and Vicon torque values between the two days of testing. The results show an overall ICC of 0.98 for the kinematic calculation of knee torque when comparing the mean stimulated torque for all conditions. The overall ICC of the Biodex dynamometer was 0.95. When accounting for stimulation frequency, 20 and 80 Hz torque showed good test-retest reliability on the Biodex with ICCs of 0.86. 20 Hz stimulation, as calculated by kinematic analysis, was moderately reliable with an ICC of 0.70; however, 80 Hz stimulation scored borderline excellent with an ICC of 0.90. A Bland-Altman plot was used to evaluate the agreement between separate measurement days for each method. The results determined good agreement for each method, with only one data point falling outside the agreement lines for both the Biodex and the Vicon overall. For Biodex, only two data points for 20 Hz and one data point for 80 Hz fell outside of the lines of agreement when evaluated separately. Bland Altman Plots for both Biodex and Vicon are shown in Figure 3. Values for Cronbach's Alpha are reported in Table 2. Pearson's correlation coefficient was 0.90 when comparing the isometric and concentric torque across all muscles and both stimulation frequencies.

Stimulated Torque Between Sessions, Muscles, and Methods. Stimulated torque (20- and 80-Hz) from quadricep muscles was not different ($p \geq 0.178$) between sessions, regardless of the method or stimulation frequency. The kinematics-based stimulated torque (i.e., concentric contraction) was significantly lower than the dynamometer-based measurements (i.e., isometric contraction) for the two frequencies ($p<0.0001$ for both). Regardless of the method, 20-Hz stimulated isometric torque was not statistically different ($p=0.247$) amongst the three quadriceps muscles. However, there were differences in individual quadriceps muscle torque at 80-Hz for both methods, with the RF muscle producing greater torques (p=0.023) than the VL muscle and a statistical trend for greater torques (p=0.081) than the VM muscle.

Table 1. Individual knee extensor Day 1 and 2 torque measured by the Biodex and Vicon

	Biodex (N●m)		Vicon (N●m)	
	Day1	**Day2**	**Day1**	**Day2**
VM20	14.95 (4.1)	16.48 (4.0)	8.21 (2.3)	7.7 (0.9)
VM80	35.64 (7.5)	36.51 (6.0)	25.87 (3.5)	26.07 (2.6)
RF20	19.25 (9.3)	19.71 (6.7)	9.97 (3.4)	8.88 (1.7)
RF80	45.08 (16.9)	43.13 (9.8)	32.49 (5.2)	31.35 (5.3)
VL20	18.10 (5.5)	17.5 (4.5)	8.57 (3.2)	8.03 (1.8)
VL80	35.74 (4.7)	34.98 (5.6)	22.3 (5.2)	22.67 (4.1)

Values are means (SD); VM20: 20 Hz VM torque; VM80: 80 Hz VM torque; RF20: 20 Hz RF torque; RF80: 80 Hz RF torque; VL20: 20 Hz VL torque; VL80: 80 Hz VL torque.

Table 2. Intraclass Correlation (ICC), Cronbach's Alpha, Limits of Agreement, and Pearson's Correlation Coefficient (r) for the Biodex and Vicon torque

	ICC (95% IC)	Cronbach's Alpha	Limits of Agreement±SD	Correlation	Significance
	Biodex				
Total	0.95 (0.90-0.97)	0.94	0.78±11.37	r=0.92	p<0.001
20Hz	0.86 (0.67-0.94)	0.85	-0.46±8.31	r=0.77	p<0.001
80Hz	0.86 (0.67-0.94)	0.85	0.62±13.88	r=0.79	p<0.001
	Vicon				
Total	0.98 (0.96-0.99)	0.98	0.50±5.76	r=0.96	p<0.001
20Hz	0.70 (0.29-0.88)	0.71	0.75±4.38	r=0.68	p<0.001
80Hz	0.90 (0.76-0.96)	0.90	0.19±6.88	r=0.83	p<0.001

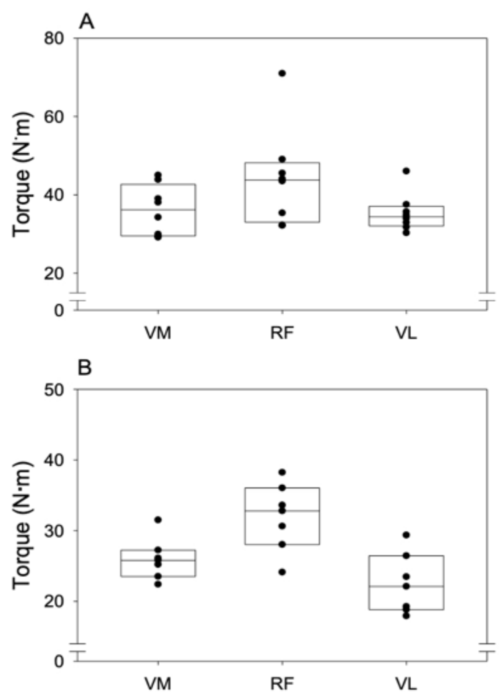

Figure 2. Distribution of high frequency (80 Hz) individual quadriceps muscle stimulated torque. (A) Box plot of 80 Hz stimulated isometric torque. (B) Box plot of 80 Hz stimulated concentric torque. VM: vastus medialis; RF: rectus femoris; VL: vastus lateralis.

DISCUSSION

Results from the current study indicated a high degree of reliability when using stimulation to generate individual knee extensor torque. Both the Biodex and Vicon scored high intraclass correlation coefficients (>0.90), representing excellent reliability (19). When evaluated separately for stimulation frequencies, the Biodex was considered reliable for both 20 and 80 Hz with ICCs of 0.86. 80 Hz stimulation calculated from Vicon motion capture was also considered reliable, with an ICC of 0.90. However, at 20 Hz, Vicon motion capture was found to have only moderate reliability with an ICC of 0.70. The Biodex reliability for measuring individual muscle force seems more consistent across the range of stimulation frequencies, but both would be considered reliable across two time points for measuring force production in individual knee extensor muscles.

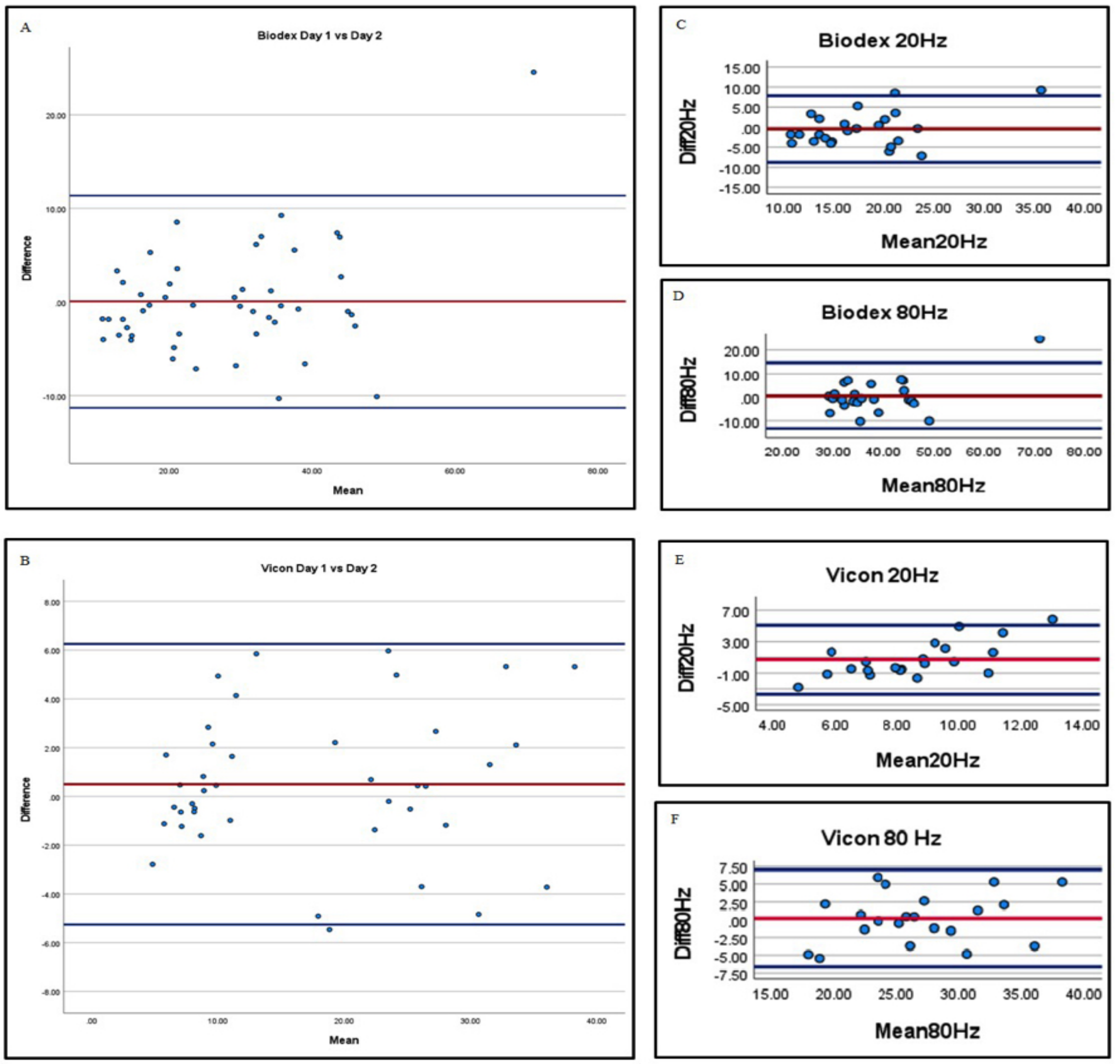

Figure 3. Bland-Altman Plots comparing Day 1 and 2 torques for the (A) Biodex dynamometer and (B) Vicon motion capture. (C-F) Bland-Altman plot comparisons for Day 1 and Day 2 torque separated by stimulation frequency. The red lines represent the mean difference between Day 1 and Day 2 values. The blue bars represent the 95% agreement lines (Mean difference ±1.96 SD).

Before this study, low and high-frequency stimulated torques were not compared across individual human knee extensor muscles. The ability to quantify torque in individual muscles furthers understanding of joint mechanics and potential susceptibility for injury. Akima and coworkers confirmed individual surface stimulation of a single superficial knee extensor muscle (i.e., VL) as shown by T2-weighted MRI imaging (22). The volume of skeletal muscle activated by electrical stimulation depends in part on the magnitude of electrical current, size of electrodes, distance between electrodes, and the location of the electrodes relative to the innervation zone and muscle architecture (23). Most studies document that most myofibers activated are superficial but that the activation of deeper myofibers is possible given the antidromic propagation of the action potential from the current field to most myofibers belonging to a given motor unit (23). Our study shows a strong positive correlation (r=0.90; p<0.001) in relative torque values produced by each muscle during stimulated concentric and isometric stimulations, as illustrated in Figure 4. Thus, electrical muscle stimulation could be reliably used to quantify individual muscle torque capacity following different exercise modalities and would reveal if potential strength imbalances exist across a joint that could alter mechanics, increasing the risk of secondary soft-tissue injury.

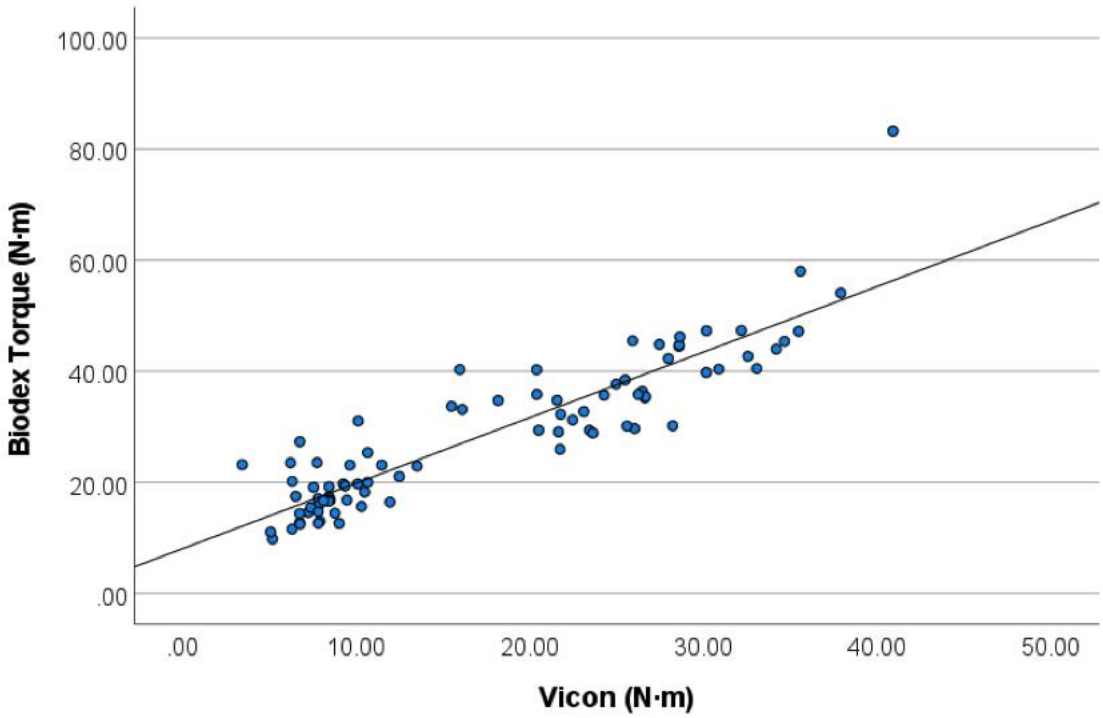

Figure 4. Relationship between mean isometric and concentric torques across each muscle and both stimulation frequencies. Pearson's r=0.902.

Strength and susceptibility to exercise-induced injury for individual skeletal muscles are mainly due to architectural differences, fiber type composition, recruitment patterns, and previous usage history (24-27). Imbalances between agonist and antagonist muscle strength increase injury susceptibility (28), but imbalances amongst individual agonist muscles have not been evaluated. Researchers and clinicians could identify pre-existing strength deficits that may predispose a person to joint instability and increased risk of injury by reliably assessing the torque of individual agonist muscles. Moreover, this approach would allow tracking individual muscle torque changes longitudinally and designing specific strengthening programs to correct imbalances - ultimately optimizing rehabilitation and reducing future injury risk.

To assess the accuracy of measuring individual quadricep muscle torque, we used published three-dimensional modeling data of resultant forces from different architectural aspects of each quadricep muscle (29) to estimate the relative contribution of each quadricep muscle to MVC isometric torque. Then, we compared the actual 80-Hz stimulated torque to the predicted torque of each muscle. Based on this approach, we estimate that the RF, VI, VM, and VL muscles contribute approximately 13.7%, 18.2%, 32.1%, and 36.1% to the MVC torque, respectively. Moreover, these predicted values of maximal force generation capacity by individual quadricep muscles are supported by physiological cross-sectional area predictions of the relative force contribution of these muscles (7, 13, 29, 30).

Stimulated 80 Hz quadricep muscle torques were not significantly different across sessions, and mean torques across days were 36.1±6.6 N•m (VM), 35.4±5.0 N•m (VL), and 44.1±13.4 N•m (RF) with forces produced by the RF muscle being significantly (p=0.023) more remarkable than the VL. It is unclear why the RF muscle produced greater torque than the other muscles despite lower reported PCSA and predicted torque, given that the electrode size and spacing were identical for the quadriceps muscles. The predicted contribution of the RF muscle to MVC torque (i.e., stimulated torque/predicted torque contribution to MVC =108.3%) suggests that additional muscle(s) may have been involved. In support of this idea, our electrode placement and size for the RF muscle may have partially activated the superficial proximal sub-branch of the femoral nerve, which lies just below the RF muscle and supplies the upper portion of the vastus lateralis muscle (13). The actual forces of the electrically stimulated (80 Hz) VM and VL muscle were 36.8% and 32.5%, respectively, of the predicted MVC forces within the predicted muscle activation volume. Therefore, we are confident that the forces produced by the VM and VL muscles were not contaminated by other muscles, partly due to visual observations of the muscle contraction during activation and the forces from these muscles correspond to our estimates of the muscle volume activated. However, it appears that the forces produced by the RF muscle may have been augmented by other muscles (i.e., VL) during stimulation.

Limitations. There are limitations to our method of evaluating individual quadriceps muscle strength. First, the percentage of myofibers recruited with each stimulation is unknown. Differences in subcutaneous adipose tissue could impact the number of motor points activated and recruited fibers. It is unlikely that all the myofibers of an individual muscle are recruited during these stimulations, and therefore, the total degree of muscle strength or injury would not be known. Despite this, the 80-Hz sum of the three tested muscles did equate to a mean of 38.9% (subject range: 28.1-48.5%) of the subjects' knee extensor MVC torque recorded during that session. Second, the validity assessment using three-dimensional modeling data of quadriceps muscle forces is from one male and two female cadavers 84±4 years of age, which does not reflect our subjects' sex (i.e., all males) and age (30.3±3.9 years). Third, we could only measure the torque produced by the three superficial muscles of the quadriceps muscle group since the vastus intermedius runs deep to the rectus femoris. Finally, the inability to know the degree of activated myofibers in neighboring agonist muscles during each stimulation may contribute to inaccurate individual muscle torque data.

CONCLUSION

The Biodex dynamometer and kinematic-kinetic analyses presented excellent overall test-retest reliability when measuring for stimulated individual muscle torque. The Biodex presented good repeatability at both frequencies, while kinematic analysis had only moderate reliability at 20 Hz but good reliability at 80 Hz. Both methods can be reliable in measuring individual skeletal muscle force during stimulated contractions.

APPLICABLE REMARKS

- The study confirms that the Biodex dynamometer and Vicon motion capture system are reliable tools for assessing individual quadriceps muscle strength in sedentary males.
- The Biodex shows consistent reliability across frequencies, and the Vicon excels at higher frequencies.
- These methods should be further developed and standardized for longitudinal tracking and targeted rehabilitation programs, particularly for addressing muscle-specific strength deficits and imbalances that can occur from fatigue and injury.
- This reliability supports their broader application in various populations and clinical settings.

AUTHORS' CONTRIBUTIONS

Study concept and design: Christopher L Rawdon, Christopher P Ingalls, Feng Yang, Jeff S Otis, Kyle Brandenberger, Mekensie Jackson. Acquisition of data: Christopher L Rawdon, Christopher P Ingalls, Mekensie Jackson. Analysis and interpretation of data: Christopher L Rawdon, Christopher P Ingalls, Feng Yang, Jeff S Otis, Kyle Brandenberger, Mekensie Jackson. Drafting the manuscript: Christopher L Rawdon, Christopher P Ingalls, Feng Yang, Jeff S Otis, Kyle Brandenberger, Mekensie Jackson. Critical revision of the manuscript for important intellectual content:

Christopher L Rawdon, Christopher P Ingalls, Feng Yang, Jeff S Otis, Kyle Brandenberger, Mekensie Jackson. Statistical analysis: Christopher L Rawdon, Christopher P Ingalls, Feng Yang, Jeff S Otis, Kyle Brandenberger, Mekensie Jackson. Administrative, technical, and material support: Christopher L Rawdon, Christopher P Ingalls, Feng Yang, Jeff S Otis, Kyle Brandenberger, Mekensie Jackson. Study supervision: Christopher L Rawdon, Christopher P Ingalls, Feng Yang, Jeff S Otis, Kyle Brandenberger, Mekensie Jackson.

CONFLICT OF INTEREST

The authors do not have declarations of interest to declare.

FINANCIAL DISCLOSURE

The authors have no financial interests or conflicts to report.

FUNDING/SUPPORT

This research was not funded or supported by internal or external funding.

ETHICAL CONSIDERATION

This research was approved by the Georgia State University Institutional Review Board (IRB Number: H20435), and all experimental procedures conformed with the Declaration of Helsinki. All subjects provided informed consent before participating in the study.

ROLE OF THE SPONSOR

This research was not sponsored.

ARTIFICIAL INTELLIGENCE (AI) USE

Artificial intelligence (AI) was not used in any capacity to develop, draft, or edit any writing, nor was it used in data processing and analysis.

REFERENCES

1. Warren G, Ingalls C, Lowe D, Armstrong R. Excitation-contraction uncoupling: major role in contraction-induced muscle injury. Exerc Sport Sci Rev. 2001;29:82-87. [doi:10.1097/00003677-200104000-00008] [PMid:11337828]
2. Warren G, Ingalls C, Lowe D, Armstrong R. What mechanisms contribute to the strength loss that occurs during and in the recovery from skeletal muscle injury? J Orthop Sports Phys Ther. 2002;32:58-64. [doi:10.2519/jospt.2002.32.2.58] [PMid:11838581]
3. Prior B, Jayaraman R, Reid R, Cooper T, Foley J, Dudley G, Meyer R. Biarticular and monoarticular muscle activation and injury in human quadriceps muscle. Eur J Appl Physiol. 2001;85:185-190. [doi:10.1007/s004210100434] [PMid:11513314]
4. Black C, McCully K. Muscle injury after repeated bouts of voluntary and electrically stimulated exercise. Med Sci Sports Exerc. 2008;40:1605. [doi:10.1249/MSS.0b013e3181788dbe] [PMid:18685531]
5. Maeo S, Saito A, Otsuka S, Shan X, Kanehisa H, Kawakami Y. Localization of muscle damage within the quadriceps femoris induced by different types of eccentric exercises. Scand J Med Sci Sports. 2018;28:95-106. [doi:10.1111/sms.12880] [PMid:28314055]
6. Beato M, Madruga-Parera M, Piqueras-Sanchiz F, Moreno-Pérez V, Romero-Rodriguez D. Acute Effect of Eccentric Overload Exercises on Change of Direction Performance and Lower-Limb Muscle Contractile Function. J Strength Cond Res. 2021;35:3327-3333. [doi:10.1519/JSC.0000000000003359] [PMid:31490430]
7. Hultman E, Sjöholm H, Jäderholm-Ek I, Krynicki J. Evaluation of methods for electrical stimulation of human skeletal muscle in situ. Pflügers Archiv. 1983 Jul;398:139-41. [doi:10.1007/BF00581062] [PMid:6622220]
8. Newham D, Mills K, Quigley B, Edwards R. Pain and fatigue after concentric and eccentric muscle contractions. Clin Sci. 1983;64:55-62. [doi:10.1042/cs0640055] [PMid:6822050]
9. Brown S, Child R, Donnelly A, Saxton J, Day S. Changes in human skeletal muscle contractile function following stimulated eccentric exercise. Eur J Appl Physiol Occup Physiol. 1996;72:515-521. [doi:10.1007/BF00242284] [PMid:8925825]
10. Mackey A, Rasmussen L, Kadi F, Schjerling P, Helmark I, Ponsot E, Agaard P, Durigan J, Kjaer M. Activation of satellite cells and the regeneration of human skeletal muscle are expedited by ingestion of nonsteroidal anti-inflammatory medication. FASEB J. 2016;30:2266-2281. [doi:10.1096/fj.201500198R] [PMid:26936358]
11. Kamandulis S, de Souza Leite F, Hernández A, Katz A, Brazaitis M, Bruton J.D, Venckunas T, Masiulis N, Mickeviciene D, Eimantas N, Subocius A. Prolonged force depression after mechanically demanding

contractions is largely independent of Ca2+ and reactive oxygen species. FASEB J. 2017;31:4809-4820. [doi:10.1096/fj.201700019R] [PMid:28716970]

12. Kamandulis S, Muanjai P, Skurvydas A, Brazaitis M, Sniečkus A, Venckūnas T, Streckis V, Mickeviciene D, Jones DA. The contribution of low-frequency fatigue to the loss of quadriceps contractile function following repeated drop jumps. Experimental physiology. 2019;104:1701-10. [doi:10.1113/EP087914] [PMid:31420978]
13. Botter A, Oprandi G, Lanfranco F, Allasia S, Maffiuletti NA, Minetto MA. Atlas of the muscle motor points for the lower limb: implications for electrical stimulation procedures and electrode positioning. Eur J Appl Physiol. 2011;111:2461-2471. [doi:10.1007/s00421-011-2093-y] [PMid:21796408]
14. Vieira TM, Potenza P, Gastaldi L, & Botter A. Electrode position markedly affects knee torque in tetanic, stimulated contractions. Eur J Appl Physiol. 2016;116:335-342. [doi:10.1007/s00421-015-3289-3] [PMid:26526290]
15. Visscher RM, Rossi D, Friesenbichler B, Dohm-Acker M, Rosenheck T, Maffiuletti NA. Vastus medialis and lateralis activity during voluntary and stimulated contractions. Muscle & Nerve. 2017;56:968-74. [doi:10.1002/mus.25542] [PMid:28029696]
16. Behm DG, Colwell EM, Power GMJ, et al. Transcutaneous electrical nerve stimulation improves fatigue performance of the treated and contralateral knee extensors. Eur J Appl Physiol. 2019;119:2745-2755. [doi:10.1007/s00421-019-04253-z] [PMid:31696316]
17. Miyamoto N, Fukutani A, Yanai T, Kawakami Y. Twitch potentiation after voluntary contraction and neuromuscular electrical stimulation at various frequencies in human quadriceps femoris. Muscle & Nerve. 2012;45(1):110-5. [doi:10.1002/mus.22259] [PMid:22190316]
18. De Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech. 1996;29(9):1223-1230. [doi:10.1016/0021-9290(95)00178-6] [PMid:8872282]
19. Koo TK, & Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J Chiropr Med. 2016;15(2):155-163. [doi:10.1016/j.jcm.2016.02.012] [PMid:27330520]
20. Haghayegh S, Kang HA, Khoshnevis S, Smolensky MH, & Diller KR. A comprehensive guideline for Bland-Altman and intra-class correlation calculations to properly compare two methods of measurement and interpret findings. Physiol Meas. 2020;41(5):055012. [doi:10.1088/1361-6579/ab86d6] [PMid:32252039]
21. Tavakol M, & Dennick R. Making sense of Cronbach's alpha. Int J Med Educ. 2011;2:53. [doi:10.5116/ijme.4dfb.8dfd] [PMid:28029643]
22. Akima H, Foley J, Prior B, Dudley G, Meyer R. Vastus lateralis fatigue alters recruitment of musculus quadriceps femoris in humans. J Appl Physiol. 2002;92:679-684. [doi:10.1152/japplphysiol.00267.2001] [PMid:11796681]
23. Enoka RM, Amiridis IG, Duchateau J. Electrical stimulation of muscle: electrophysiology and rehabilitation. Physiology. 2019;35:40-56. [doi:10.1152/physiol.00015.2019] [PMid:31799910]
24. Lieber RL, Fridén J. Functional and clinical significance of skeletal muscle architecture. Muscle & Nerve: Official Journal of the American Association of Electrodiagnostic Medicine. 2000 Nov;23(11):1647-66. [doi:10.1002/1097-4598(200011)23:11<1647::AID-MUS1>3.3.CO;2-D]
25. de Brito Fontana H, Han SW, Sawatsky A, Herzog W. The mechanics of agonistic muscles. Journal of biomechanics. 2018;79:15-20. [doi:10.1016/j.jbiomech.2018.07.007] [PMid:30195849]
26. Han SW, Sawatsky A, de Brito Fontana H, Herzog W. Contribution of individual quadriceps muscles to knee joint mechanics. Journal of Experimental Biology. 2019;222(6). [doi:10.1242/jeb.188292] [PMid:30846537]
27. Pincivero DM, Salfetnikov Y, Campy RM, Coelho AJ. Angle-and gender-specific quadriceps femoris muscle recruitment and knee extensor torque. Journal of biomechanics. 2004;37(11):1689-97. [doi:10.1016/j.jbiomech.2004.02.005] [PMid:15388311]
28. Padasala M, Joksimovic M, Bruno C, Melino D, Manzi V. Muscle injuries in athletes. The relationship between H/Q ratio (hamstring/quadriceps ratio). Ita J Sports Reh Po. 2020;7(1):1478-98.
29. Chiu LZ, Daehlin TE. Three-dimensional modeling of human quadriceps femoris forces. J Biomech. 2021;120:110347. [doi:10.1016/j.jbiomech.2021.110347] [PMid:33711598]

30. Ward SR, Eng CM, Smallwood LH, Lieber RL. Are current measurements of lower extremity muscle architecture accurate?. Clin Orthop Relat Res. 2009;467(4):1074-1082. [doi:10.1007/s11999-008-0594-8] [PMid:18972175]