Multijoint Musculoarticular Stiffness Derived From a Perturbation Is Highly Variable

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Abstract

Schofield, M, Tinwala, F, Cronin, J, Hébert-Losier, K, and Uthoff, A. Multijoint musculoarticular stiffness derived from a perturbation is highly variable. *J Strength Cond Res* XX(X): 000–000, 2019—Testing musculoarticular stiffness may provide insights into multijoint elastic properties. Yet, most research has focused on quantifying stiffness, or elastic potential, at a single joint. The purpose of this study was to quantify the test-retest reliability of musculoarticular stiffness derived from the perturbation technique across the bench pull, bench press, and squat movements. Eight resistance-trained men performed bench pull, bench press, and squat repetition maximums, after which a perturbation protocol was tested over multiple days. During the 3 movements, a brief perturbation was applied to the bar. The resulting sinusoidal wave was measured by an underbench force plate and a linear position transducer attached to the bar. From the sinusoidal wave, stiffness was derived and found to be unreliable across movements and days (change in mean: −35.1 to 15.8%; coefficient of variation: 7.1–111%; intraclass correlation: −0.58 to −0.89). Squat data were removed from the analysis entirely because of the inability to consistently determine the perturbations on the force plate. Practitioners need to be aware that musculoarticular stiffness as measured using the perturbation technique on the movements performed in this study has considerable limitations in terms of reproducibility.

Key Words: stretch-shortening cycle, track and field, reliability, oscillation

Introduction

Shot put, discus, and hammer throw can be categorized as stretch-shortening cycle activities because eccentric actions are immediately proceeded by concentric actions, enhancing force output. These stretch-shortening cycle movements have been observed in the upper body (13,19), trunk (13,19), and lower limbs (10,12). During stretch-shortening cycle movements, musculotendinous units initially act eccentrically (i.e., stretch), where elastic energy is stored in the muscles and parallel and series elastic components and returned concentrically (i.e., shorten) at a rate and magnitude dependent on movement dynamics (e.g., system inertia and contractile epoch) and elastic properties (e.g., stiff vs. compliant). Stiffness is an important performance variable which is the relationship between the deformation of a body segment, or multiple body segments, and a given force (9). Greater stiffness is associated with less energy leakage during the stretch-shortening cycle, and therefore, enhanced force production (9).

During throwing movements, multiple segments interact at any 1 time, thus the stiffness of a singular tissue (e.g., Achilles tendon) does not tell us what is occurring with regards to the stiffness qualities at the multijoint level, i.e., lower-limb squat and upper-body press (10,12,14). However, to date, much of the research has focused on single-joint elastic properties rather than multijoint ones. Single-joint elastic properties have been shown to be reliable (intraclass correlation [ICC] = 0.88–0.98, coefficient of variation [CV] = 4.7–8.7%) (17,23,34), to distinguish between athlete groups (1,37), and relate to athletic performance (1,6,8,24); but, less is known about multijoint stiffness.

Multijoint stiffness is otherwise known as musculoarticular stiffness because the assessment does not differentiate between individual structures. One method for quantifying musculoarticular stiffness is to use a perturbation protocol, during which a brief perturbation is applied to a load, generating a sinusoidal wave which is said to represent stiffness. One research group has reported excellent test-retest reliability of musculoarticular stiffness during a bench press movement (ICC = 0.89) (31) and observed stiffness to be positively related to 1 repetition maximum (1RM) bench press performance ($r = -0.72, p < 0.01$) (33). The same research group observed a decrease in musculoarticular stiffness with an increased bench press 1RM (31). Based on these results, it seems that the natural frequency of tissue can be shifted, giving rise to the idea of regional elastic musculoarticular stiffness specificity (1,24,31). If elastic tissues exhibit stiffness that is "optimal" for a given movement, then the muscle can work closer to its optimal length and return elastic energy within the required time frames, ultimately increasing force outputs and performance (25,31).

In track and field throwing events, performance is accomplished through a series of multijoint interactions. Therefore, assessing musculoarticular stiffness may provide more practical insights into musculotendinous functioning during the actual performance tasks. However, to the best of our knowledge, the reliability of musculoarticular stiffness has only been reported using ICC measures for a bench press movement (31). The inclusion of additional movements and measures of reliability would provide a more comprehensive understanding of the variability associated with multijoint musculoarticular stiffness and

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its utility. Therefore, the purpose of this investigation was to quantify the test-retest reliability of musculoarticular stiffness derived from the perturbation technique across the bench pull, bench press, and squat movements. Given the previous literature on musculoarticular stiffness, we hypothesized that this physical characteristic would be reliable across loads and movements.

Methods

Experimental Approach to the Problem

This study used a within-subject repeated-measures design to assess musculoarticular stiffness during a bench pull, bench press, and back squat in experienced resistance-trained men over 3 occasions. The subjects participated in a familiarization session where their 1RM strength was determined for each lift, and they were familiarized with the perturbation loads, an inertial load bike, and a seated medicine ball put. Testing took place over 3 weeks, with 7 days separating each session. For each of the 3 test sessions, upper- and lower-body force capabilities were quantified from the seated medicine ball put and inertial load bike, respectively. Thereafter, the subjects performed the bench pull, bench press, and back squat using perturbation loads between 15 and 70% of 1RM. During each of the perturbation trials, force plates and linear position transducer (LPT) were used to determine bar oscillations. Based on the resultant oscillations, musculoarticular system stiffness was derived for each movement and load.

Subjects

Eight experienced resistance-trained men, aged 18-27 years (6 highly strength trained subjects and 2 elite track and field subjects) of similar strength volunteered to participate in this investigation (Table 1). Experienced resistance-trained was determined as bench press and bench pull strength greater than body mass and greater than 1.5 times body mass for the back squat. All subjects provided written consent prior to participating in this study. Subjects were not included if they were, or had used, performance-enhancing substances (WADA, 2016), and all protocols were approved by Auckland University of Technology's Institutional Research Ethics Committee.

Table 1
Subject characteristics.*

Characteristic	Units of measurement	Mean ± *SD*
Age	y	23.6 ± 3.7
Height	cm	180.4 ± 10.8
Mass	kg	90.1 ± 19.6
Squat 1RM	kg	172.8 ± 28.1
	BM	2.0 ± 0.3
Bench press 1RM	kg	112.8 ± 24.6
	BM	1.3 ± 0.2
Bench pull 1RM	kg	95.6 ± 15.5
	BM	1.1 ± 0.1

*1RM = 1 repetition maximum; BM = relative to body mass.

Procedures

Equipment. All testing was performed in a laboratory with ambient temperature set at 22°. Bar displacements were tracked by a PT5A (Fitness Technologies, SA, Australia) LPT connected to a barbell, synchronized with 2 AccuPower (Advanced Medical Technology, Inc., [AMTI] Watertown, MA) force plates to collect ground reaction force data. All devices were synchronized and collected at 1,000 Hz using a custom LabView (LabView Professional 2016) program.

Familiarization and One Repetition Maximum Testing. During the testing, subjects were asked to maintain regular dietary, hydration, and sleep behaviors and refrain from intense resistance activity for 48 hours before testing. All subjects attended 4 testing sessions (1 × familiarization and 3 × data collection) at the same time of day, with each testing occasion separated by 7 days. The initial familiarization session included the collection of baseline data (height, mass, and age), determination of 1RM strength for each of the lifts, multiple perturbation trials at loads between 20 and 60 kg, and familiarization with the inertial load bike and seated medicine ball put. All subjects were familiar with 1RM testing, during which multiple warm-up sets at increasing loads were performed, and once ~90% repetition was reached 5–10 kg, increments in load were used to establish the 1RM (7). One repetition maximum was established in <5 repetitions after warm-up loads. The order of 1RM testing was bench pull, bench press, and back squat, respectively. Spotters and spotting bars were used across loads and lifts to ensure safety. A minimum recovery time of 120 seconds was implemented between attempts and exercises to limit the effect of fatigue.

Warm-up and Premeasures. On arrival to all testing occasions, subjects performed 5 minutes of low-intensity cycling, followed by 10 leg swings (both flexion/extension and abduction/adduction), lunges, push-ups, T-Y-W scapulae retraction movements, and open book torso rotations. After the warm-up, 3 maximal inertial load bike trials and 3 maximal seated medicine ball puts at 3- and 5-kg loads were performed to determine the force capabilities of the upper and lower body and to compare the subjects' contractile state between sessions. Briefly, the inertial load bike trials were performed on a custom-made bike with a fixed-weight (31.9-kg) flywheel and crank length (165 mm). Seat height was adjusted to a position where slight knee flexion was observed at the bottom of the pedal stroke and handle bar height to a position of comfort. Seat and handle bar heights were recorded and kept constant across days. The trial consisted of an 8-revolution maximal effort from which peak power, peak torque, revolutions per minute, and optimal cadence were derived. During the seated medicine ball put, subjects were strapped into a seat that limited hip movement. Holding the medicine ball in their dominant hand, each subject put the ball using a countermovement action as far as possible. Dominant hand was defined as the hand in which the subject preferred to put the medicine ball with. Three trials at each load starting with the 3-kg ball were performed. Three electronically synchronized cameras (Camera, Vision Prosilica GX1050C; Allied Vision, Exton, PA; frame rate; 70 fps, shutter speed; 1/1,000) recorded each put using custom-written software (HPSNZ portable tracker; HPSNZ, Auckland, New Zealand). Before data collection, all cameras were calibrated following the manufactures' procedure. Cameras were fixed behind (4.2 m behind, 1.0 m high), to the right (3.7 m right, 0.99 m high), and above (5.0 m above) the subject. The center of the medicine ball was manually digitized in each frame within the custom-written software. Velocity and accelerations were calculated from position and time traces and filtered at 8 Hz using a low-pass Butterworth filter. Cutoff frequency was determined using residual analysis.

Bench Press. A countermovement bench press was used consistent with previously described methods (3,4,33). Briefly, lying

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supine on a bench press, the Olympic bar was lowered to the chest at a self-selected speed, followed immediately by a concentric press. Before the execution of the lift, grip width was determined as width needed to have the forearm perpendicular to the floor when the bar rested on the chest, and the humerus abducted 70° (referenced from the anatomical position). Trials during which the head, shoulders, hips, or feet lost contact with their respective support surfaces (bench or force plate) or with excessive bouncing of the barbell were disregarded and repeated. In addition, light contact with the chest, roughly level with the lower chest, was cued. To collect ground reaction force and barbell data simultaneously, the bench press and subjects were positioned spanning across 2 AMTI force plates synchronized to the LPT that was attached as centrally as possible to the barbell (Figure 1).

Bench Pull. A countermovement bench pull consistent with the methods detailed by Sanchez-Medina et al. (27) was performed, although a Smith machine was not used. Briefly, lying prone on a high-pull bench, a grip position consistent with that of the bench press was attained using bar markings. Before the first repetition, the Olympic bar was held above an extended arm position with elbows flexed. Once released, the bar was lowered to the extended arm position. Subjects then rowed the bar into the bench making contact with a point coinciding with the xiphoid process. This method allowed for countermovement repetitions. The contact point on the bench was 7 cm below the xiphoid process because of the steel frame. Cues were given to contact the bench as forcefully as possible, and only trials where contact was made were counted. Trials during which the chin, chest, or hips lifted off the bench were disregarded and repeated. To collect kinetic and kinematic data, the bench pull was placed on 2 synchronized AMTI force plates with the LPT attached as centrally as possible to the barbell (Figure 2).

Back Squat. A countermovement back squat consistent with previous investigations (5,28) was performed. Starting in an erect position with an Olympic bar securely resting on the upper back, subjects squatted down to a soft deformable hurdle placed at a height consistent with a 90° knee angle (21). After a light touch, cues were given to drive up explosively. A 90° knee angle was used because it corresponds to the knee angle observed in the power position during shot put and discus (35). Squatting belts were allowed if requested. Trials where a 90° knee flexion angle was not achieved were disregarded and repeated. To collect kinetic and kinematic data, all repetitions were performed standing on an AMTI force plate with an LPT attached as centrally as possible to the barbell Figure 3.

Perturbation Method. Loads concurrent with those used by Wilson et al. (32) were used (perturbations at 15, 30, 45, 60, and 70% of 1RM) across movements. All loads were rounded to the nearest kilogram. For all 3 movements assessed, the perturbation was applied 3 cm above the maximal eccentric range of motion. As such, the bar was lowered and held isometrically for less than 2 seconds, 3 cm off the chest during the bench press, 3 cm above full elbow extension/shoulder adduction/protraction during the bench pull, and 3 cm above the deformable hurdle that marked the 90° knee angle during the squat. At this position, a perturbation of ~100 N was applied by a sharp press with the assessor's hand to the center of the barbell. Manual application of force to the barbell results in slight variation in perturbation magnitude between trials; however, stiffness is invariant as an elastic system oscillates at its resonant frequency (32). To standardize the protocol as much as possible, the same assessor applied the perturbation and practiced the perturbation method on the force plate.

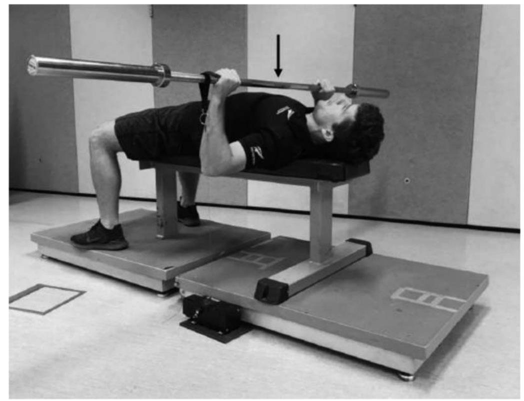

Figure 1. Bench press perturbation set-up. Arrow denotes point of perturbation application.

Subjects were instructed to maintain an isometric position and "to not respond" to the perturbation to limit voluntary input (18,32,33). Furthermore, subjects were blinded to the perturbation by visually obstructing them from seeing the barbell as per the recommendations of Ditroilo et al. (15). Back squat perturbation data were not considered during analysis because of the inability to consistently determine the perturbations on the force plate and identify an oscillation pattern.

Musculoarticular Stiffness Calculation. Musculoarticular system stiffness (Nm) of the system was determined using methods identical to those previously detailed by Wilson et al. (32) and Ditroilo et al. (15). Calculations were made from the initial damped oscillation cycle recorded. From the oscillation recordings and known constants, stiffness (k) was calculated as:

$$k = 4m f^2 \pi^2 + c^2/4m,$$

where m, f, and c represent the mass, damped natural frequency, and damping coefficient. The frequency of oscillation was quantified as the inverse of the period between successive force peaks. The damping ratio (s) was determined by plotting the natural log of force peaks against time, thereby obtaining the slope of the line. The damping coefficient (c) was then calculated as:

Figure 2. Bench pull perturbation set-up. Arrow denotes point of perturbation application.

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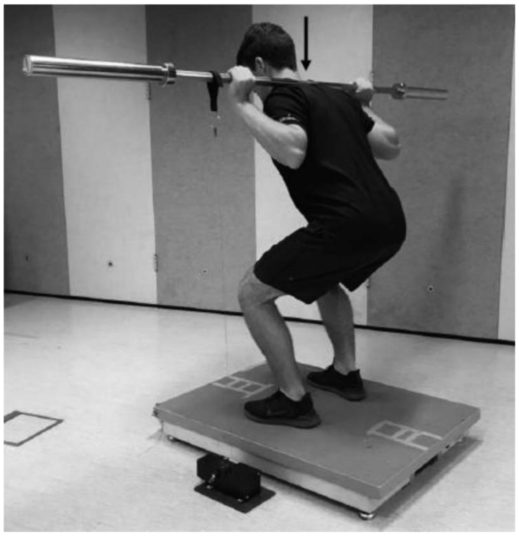

Figure 3. Back squat perturbation set-up. Arrow denotes point of perturbation application.

$$c = 4\pi m(f')s,$$

where the natural frequency is given by:

$$(f') = \left[f^2/\left(1 - s^2\right)\right].^{1/2}.$$

Data Analyses. The data were analyzed using MATLAB 2018a (Massachusetts, USA). First, the raw data were filtered using a low-pass Butterworth filter. The LPT and force plate data were filtered using a cutoff frequency of 8 and 15 Hz, respectively. Cutoff frequencies were determined using residual analysis (36). The perturbation was identified in the LPT data using a custom peak detection algorithm, which was time synchronized with the force plate data. The force plate data showed racking and unracking artifacts, which made it difficult to identify the perturbation signal correctly. The LPT was added to remove any ambiguity because it identified the "unrack," "perturbation," and "rerack" time points clearly. A second custom peak detection algorithm was used to identify the peaks in the oscillatory force signal (Figure 4A). The first 2 peaks and their times were used to calculate the slope ($Nm{\cdot}s^{-1}$), period (s) and damped frequency (f_d) (Figure 4B). The stiffness and natural frequency metrics were calculated, as described above.

$$\text{Slope} = \frac{\text{Peak 2} - \text{Peak 1}}{\text{Time 2} - \text{Time 1}} = Nm{\cdot}s^{-1},$$

$$\text{Damped frequency} = \frac{1}{\text{Period}},$$

$$f_d = \frac{1}{\text{Time 2} - \text{Time 1}}.$$

Statistical Analyses

Reliability was quantified using the methods described by Hopkins (20) to calculate the change in mean (CM) as a percentage fluctuation in the overall mean, CV to quantify the typical error as a percentage of each subject's mean, and the ICC to indicate the consistency of measures of subjects in relation to their ranking in the group. Reliability thresholds of CV $\leq$10% (Atkinson and Nevill, 1998) and ICC $\geq$ 0.70 (Meylan et al. 2012) were used as indicators of acceptable reliability. Two-tailed paired *t*-tests were used to determine significant differences between testing days on the means of each performance variable, with the level of significance set a priori at $p \leq 0.05$.

Results

Inertial Load Bike and Medicine Ball Put

All inertial load and seated medicine ball put variables were observed to be highly reliable (inertial load bike: ICC, 0.69–1.00; CV, 1.2–5.6%; CM −2.6 to 2.1%; seated medicine ball put: ICC, 0.82–0.95; CV 2.7–6.8%, CM −3.7 to 0.7%). No significant difference between days was observed for any of the inertial load bike variables and 3-kg medicine ball put peak velocity and acceleration measures (Table 2). However, a significant decrease in 5-kg medicine ball put peak velocity, but not acceleration, was observed from day 1 to day 2.

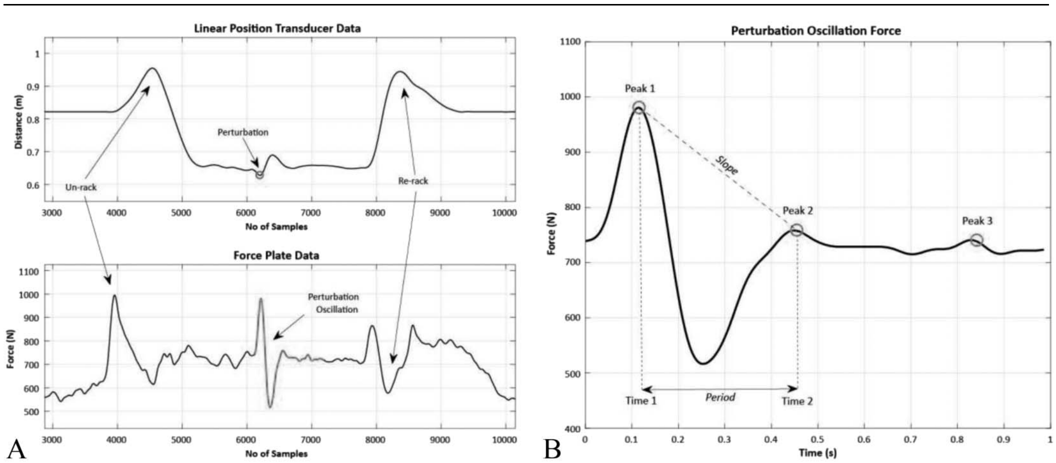

Figure 4. A) Linear position transducer signal used to determine perturbation onset. B) Peak identification to calculate natural frequency and stiffness.

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Table 2
Inertial load bike and seated medicine ball output variable mean data.*

Variable	Mean ± *SD* Day 1	Day 2	Day 3
Inertial load bike			
Peak power (W)	1,489 ± 347	1,449 ± 287	1,439 ± 280
Optimal cadence (rpm)	132.6 ± 6.6	129.3 ± 9.0	131 ± 8.0
Maximum torque (Nm)	201.9 ± 56.6	205.7 ± 53.8	201 ± 50.4
Maximal cadence (rpm)	264.9 ± 24.6	265.2 ± 25	271 ± 27.1
Seated medicine ball put			
3-kg peak velocity ($m \cdot s^{-1}$)	8.0 ± 0.95	7.8 ± 0.8	7.7 ± 0.8
3-kg peak acceleration ($m \cdot s^{-2}$)	47.4 ± 6.7	45.7 ± 6.1	46.0 ± 6.4
5-kg peak velocity ($m \cdot s^{-1}$)	6.7 ± 0.97	6.5 ± 0.69†	6.3 ± 0.71
5-kg peak acceleration ($m \cdot s^{-2}$)	35.5 ± 5.3	33.0 ± 5.0	32.3 ± 4.3

*rpm = revolutions per minute.
†Significant differences days 1–2.

Bench Press

Bench press stiffness data are presented in Table 3. The CM between days ranged from −35.1 to 15.8%, with a decrease observed from day 2 to day 3. No systematic change in CV (range: 16.1–111%) or ICC (range: −0.58 to 0.75) between days or across loads were observed.

Bench Pull

Bench pull stiffness data are detailed in Table 3. The CMs between days ranged from −16.9 to 11.1%, with no observable systematic change. No systematic change in CV (range: 7.07–40.6%) or ICC (range: −0.15 to 0.89) between days or across loads was observed. Only the musculoarticular stiffness measure from the bench pull at 60 and 70% of 1RM between day 1 and day 2 demonstrated an acceptable reliability based on the CV and ICC values.

Discussion

Musculoarticular stiffness is believed to be an important indicator of performance and tissue adaptation (6,24,33). The purpose of this investigation was to establish whether measures of stiffness through the perturbation technique were reproducible using the bench pull, bench press, and squat movements. The main findings were an inability to quantify any stiffness data for the squat movement, and that bench pull and bench press musculoarticular stiffness measures did not meet the pre-established thresholds of acceptable reliability (ICC > 0.70 and CV < 10%) across the 3 experimental days. These findings do not support our hypothesis, yet provide important insights into the use of musculoarticular stiffness testing for upper- and lower-body movements.

Variability in data between testing sessions can be attributed to several sources, either technological error, biological change, or an inherent variability in the assessment. In the current investigation, force plates and LPT were powered before testing sessions to adjust to ambient conditions, calibrated, and zeroed to reduce technological error. Testing was undertaken 7 days apart at a similar time of day to avoid diurnal fluctuations in performance, with identical warm-up performed before testing. In addition, to compare contractile state between sessions, maximal inertial load bike and seated medicine ball put measures were taken. A significant decrease in 5-kg medicine ball put peak velocity was noted on day 2, with no change in any of the other maximal measures. These data would suggest similar muscular and biological status between days. The lack of correspondence between muscular output and musculoarticular stiffness measures between days leads us to conclude that the variability in musculoarticular stiffness can be attributed to the variability in the assessment itself.

This is the first study to the best of our knowledge to attempt to quantify the musculoarticular stiffness associated with the squat movement using a perturbation technique. We were unable to measure stiffness from the squat movement because of an inability to identify an oscillatory pattern at the force plate. The LPT was used to determine the timing of the perturbation because movement in a sine wave on a force plate can be generated without visible change in bar displacement. It would seem that during the squat, the perturbation applied to the bar was dampened through the entire proximal-distal musculoskeletal system to the point that minimal or no sine wave was discernible at the force plate.

Wilson et al. (31) reported test-retest reliability of musculoarticular stiffness to be high for the bench press movement (ICC = 0.89), which contrasts to our bench press data (ICC < 0.70, CV > 10%). Similar to the study by Wilson et al. (31), experienced resistance-trained subjects were involved in this study; however, we here report raw stiffness data vs. predicted stiffness from an exponential curve. We observed greater maximal stiffness than that reported by Wilson et al. (33) (stiffness: 12,015–27,677 $N \cdot m^{-1}$); however, our stiffness values largely fall within the 10,000–50,000

Table 3
Bench press and bench pull musculoarticular stiffness (Nm) data and reliability metrics across days.*

% RM	Mean ± *SD* Day 1	Day 2	Day 3	Change in mean (%) Days 1–2	Days 2–3	CV (%) Days 1–2	Days 2–3	ICC Days 1–2	Days 2–3
Bench press									
15% RM	7,858 ± 4,254	5,129 ± 1,138	5,295 ± 891	−29.3	4.22	31.4	16.1	0.50	0.53
30% RM	16,589 ± 7,636	11,595 ± 7,599	10,491 ± 3,641	−35.1	1.99	54.2	35.8	0.38	0.65
45% RM	14,657 ± 5,946	14,147 ± 4,741	15,084 ± 5,927	−3.7	7.16	60.1	47.7	−0.58	−0.04
60% RM	−11,054 ± 100,687	20,942 ± 12,386	20,997 ± 12,778	−9.33	−1.81	37.2	45.6	0.75	0.59
70% RM	21,678 ± 7,211	38,314 ± 53,393	35,520 ± 37,430	10.8	15.8	78.1	111	0.43	0.28
Bench pull									
15% RM	8,896 ± 4,219	7,157 ± 2,539	7,492 ± 1,613	−16.0	8.77	27.4	26.7	0.67	0.46
30% RM	17,471 ± 6,104	15,499 ± 4,712	13,909 ± 2,873	−10.2	−8.42	40.6	14.7	−0.15	0.79
45% RM	18,871 ± 4,996	18,436 ± 3,774	17,960 ± 3,313	−1.68	−2.19	19.9	10.3	0.29	0.79
60% RM	21,279 ± 3,711	21,409 ± 2,273	18,097 ± 4,082†	1.46	−16.9	7.07	14.3	0.84	0.50
70% RM	23,135 ± 5,441	22,465 ± 4,380	27,066 ± 15,844	−2.19	11.1	8.38	33.8	0.89	0.24

*CV = coefficient of variation; ICC = intraclass correlation coefficient; % RM = percentage of 1 repetition maximum.
†Significant differences days 2–3.

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$N \cdot m^{-1}$ reported in lower-body musculature. Subject characteristics may explain our greater stiffness values. The subjects used in this study ranged from trained strength athletes to elite track and field throwers, which likely possess greater stiffness than untrained subjects (22). Alternatively, the large variation in stiffness values may relate to the poor reliability of the method and inability to control for neural input (conscious and reflex) on stiffness.

In our study, the reliability of musculoarticular stiffness values in an upper-body pulling-type movement (bench pull) was better than that of a pressing-type movement (bench press), although both failed to reach the thresholds of acceptable reliability. Stiffness was higher than that previously reported in the literature (31,33). The nature of the movement involved tissue affect stiffness (21,24), which is another likely source of between-study differences. Little data are available regarding pulling movements and musculoarticular stiffness, limiting the ability to make strong inferences. Further research is required to understand physiological elastic variability among tissues involved in pulling movements and throughout the body.

In the context of rotational throwing, elastic return of all involved tissues rather than the return of a particular structure is of importance to the outcome of the movement. Both elastic and contractile structures play an integral role in the storage and transfer of elastic energy during multijoint movements (11,16,29,30). However, most assessments quantifying elastic resonant frequencies and stiffness describe the elastic properties of isolated elastic structures (21,24). No reliable method to quantify multijoint elastic properties across the body currently exists in vivo. Quantifying the mechanical properties of elastic structures in compound movements could be of benefit to sports performance; however, as demonstrated by the current study, the ability to repeatedly quantify natural frequency and musculoarticular stiffness in compound upper- and lower-body movements is poor. Further research should look to refine both bench press and bench pull perturbation protocols, or develop alternative methods to quantify elastic properties of movement patterns noninvasively that can be used to inform strength and conditioning practices. Alternative methods may include measuring natural frequency individual limbs during compound movement perturbations through accelerometry or perturbing from different locations such as a belt squat during the squat protocol.

Practical Applications

These data suggest that quantifying musculoarticular stiffness during a bench press, bench pull, or squat movements is unreliable across multiple days and loads. Predicting stiffness from a regression curve may increase the reliability because it aids in reducing the impact of outliers on the data; however, the reproducibility of the raw data needs to be improved if practitioners wish to use this method. Familiarization with the protocol beyond 1 session seems to make little difference to reliability. Therefore, changes to the methodology or development of alternative methods are required. Future investigations should seek to refine perturbation protocols to increase the reliability of measures because musculoarticular stiffness has practical implications for strength and conditioning practitioners and sports performance.

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