7-29-2019

Reliability of squat kinetics in well-trained rugby players: Implications for monitoring training

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10.1519/JSC.0000000000003289
This is an authors accepted manuscript of: Appleby, B.B., Cormack, S.J., & Newton, R.U. (2019). Reliability of squat kinetics in well-trained rugby players: Implications for monitoring training. *Journal of Strength and Conditioning Research*. 33(10) 2635–2640.

ABSTRACT

The aim of this study was to determine the within-session reliability in kinetic variables of the squat in well-trained athletes during a typical resistance training protocol. Fifteen subjects completed two testing sessions. Session one was establishment of one repetition maximum (1RM) squat and session two involved two sets of two maximal effort repetitions of the squat at 70%, 80% and 90% of 1RM with 3D motion analysis and ground reaction force (GRF) measurement using two in-ground tri-axial force plates. Reliability was calculated using typical error ± 90% confidence limits (CL), expressed as the coefficient of variation (CV%) and intraclass correlation coefficient (ICC). The smallest worthwhile change (SWC%), calculated as 0.2 x between-subject standard deviation was used to determine the smallest important change in performance. Peak and average GRF were found to have acceptable measures of reliability with the combined left and right leg average GRF capable of detecting the SWC. Independent limb contributions were reliable (left and right, or dominant and non-dominant). Reliable kinetics can be obtained in back squat performance typical of a resistance training session in well-trained athletes. This suggests that coaches integrating force plate technology within training sessions may effectively capture between one and six training sets amongst several athletes, facilitating analysis and intervention on larger data sets.

Keywords: ground reaction force, biomechanics, bilateral, symmetry.

INTRODUCTION

Athletic movements of sprinting and jumping are greatly influenced by the magnitude of force and impulse applied (317, 373). Muscular strength, as an indication of force production, has been linked to superior athletic prowess (31, 490, 568, 569). The squat has long been used as a training and testing exercise of strength in multiple sport settings (32, 213, 401, 488). As a measure of general lower body strength, the squat has been demonstrated to be reliable in many environments (37, 117, 493, 558). Historically, analysis of the squat was concerned with gross measures of strength, usually maximum weight lifted, however, advances in technology in the training environment are facilitating greater kinetic monitoring and screening (469). Given the link between force application and movement, it is favourable to reliably measure force as opposed to secondary outcomes such as displacement and velocity.

Quantification of reliability is influenced by external sources of variability (e.g. instrumentation, test design) and internal sources; characteristics of the tested individual (e.g. age/experience, injury, motivation) and studies establishing reliability ensure strict protocol (97, 117, 124). Reliability assessment is typically determined between-sessions to guide practitioners to identify true performance changes (113, 291). Yet advances in technology are facilitating the recording of force plate or barbell velocity variables within training sessions. Whilst studies have investigated the bilateral kinetics of back squats, specific within -session reliability of bilateral ground reaction force (GRF) and impulse has yet to be reported, particularly in well-trained populations with high external loads, typical of athletic strength training sessions (200, 478, 536). The performance of multiple sets within a team sport strength training session potentially provides a wealth of data for coaches to monitor and refine training prescription between scheduled standardised testing. Additionally, unilateral diagnosis in bilateral squat performance may assist practitioners identify potential limitations or injury risk, or facilitate return to play rehabilitation protocols (432). However, it is currently uncertain if multiple sets of high intensity squats within a session can be reliably measured.

Technological improvements are permitting the recording and analysis of GRF in the training environment. Common practice encourages data collection to occur early in a session to minimise the influence of fatigue. However, such protocols may be impractical with large squad numbers and limited testing devices. Reliable testing practices would broaden the data capture opportunity (via force plates or barbell velocity) for coaches working with large squads permitting greater analysis and program refinement opportunities. Therefore, the purpose of this study was to determine the stability of GRF during repeated maximal intensity squat sets, typical of a resistance training protocol in well-trained athletes.

METHODS

Experimental Approach to the Problem. A cross-sectional research design was utilised to determine kinetics during the squat in trained subjects (Figure 5.1). Fifteen subjects attended two testing sessions, separated by seven to ten days. The first testing session involved assessment of one repetition maximum (1RM) strength in the back squat. The second testing session involved biomechanical assessment of the back squat. At this session, subjects performed two sets of two repetitions of the back squat at 70%, 80% and 90% of 1RM. Force application and movement patterns were assessed using tri-axial force plates and three-dimensional motion measurement.

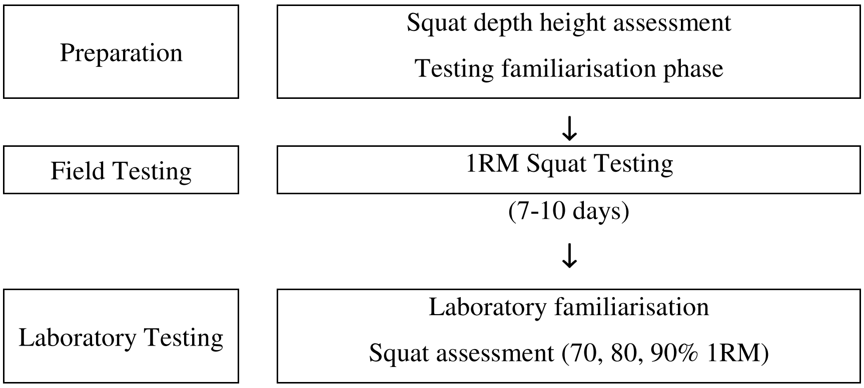

Figure 5.1: Schematic representation of experimental design (1RM = one repetition maximum)

*Subjects***.** A combination of 15 academy and professional rugby union players were recruited to participate in this investigation (Table 5.1). All subjects were notified of the potential risks involved and gave their written informed consent. This study was approved by the University's Human Research Ethics Committee. All subjects were cleared by medical staff to be free of serious lower limb injury in the previous six months or injury history which may have inhibited performance. Data was captured during a non-competitive period and subjects permitted to train, with testing aligned to rest days to ensure minimal fatigue during assessment. Subjects were required to attend the testing well hydrated.

Table 5.1. Subject characteristics.

Age (years)	Body weight (kg)	Height (cm)	90° Squat 1RM (kg)	Relative squat (1RM : BW)
24.1 ± 3.0	103.6 ± 9.5	185.5 ± 5.8	195.7 ± 27.6	1.90 ± 0.13

Data presented as mean ± SD for all variables. **kg:** kilograms; **cm:** centimetres; **1RM**: one repetition maximum; **1RM:BW**: 1RM divided by subject bodyweight

Procedures. *Squat Assessments.* Subjects were allocated a 90° knee angle squat depth (a line from the greater trochanter to the lateral condyle, and the lateral condyle to the lateral malleolus) during familiarisation using a goniometer with video analysis confirmation. An elastic strap was attached horizontally across a power rack (York Fitness, Rocklea, Queensland, Australia) at each subjects' individually determined depth. The 1RM testing (based on a previous protocol (377)) required subjects to perform a series of warm-up sets (four repetitions at 50% of estimated 1RM, three repetitions at 70%, two at 80% and one at 90%), each separated by three minutes recovery. Following the warm-up, a series of maximal attempts were performed, separated by five-minutes recovery. An accredited strength and conditioning (S&C) coach (Australian Strength and Conditioning Association, Level 3) and at least one assistant observed each test for safety, technique and depth monitoring. The repetition was deemed a fail if the subject could not achieve the required depth or could not return to the upright position.

Biomechanical Assessment. Session two was the biomechanical assessment of force application during the back squat. Technique was monitored according to the 1RM protocols and trials not meeting these criteria were repeated. During all trials, GRF was assessed using two tri-axial force plates and three-dimensional motion analysis. Three minutes rest separated sets.

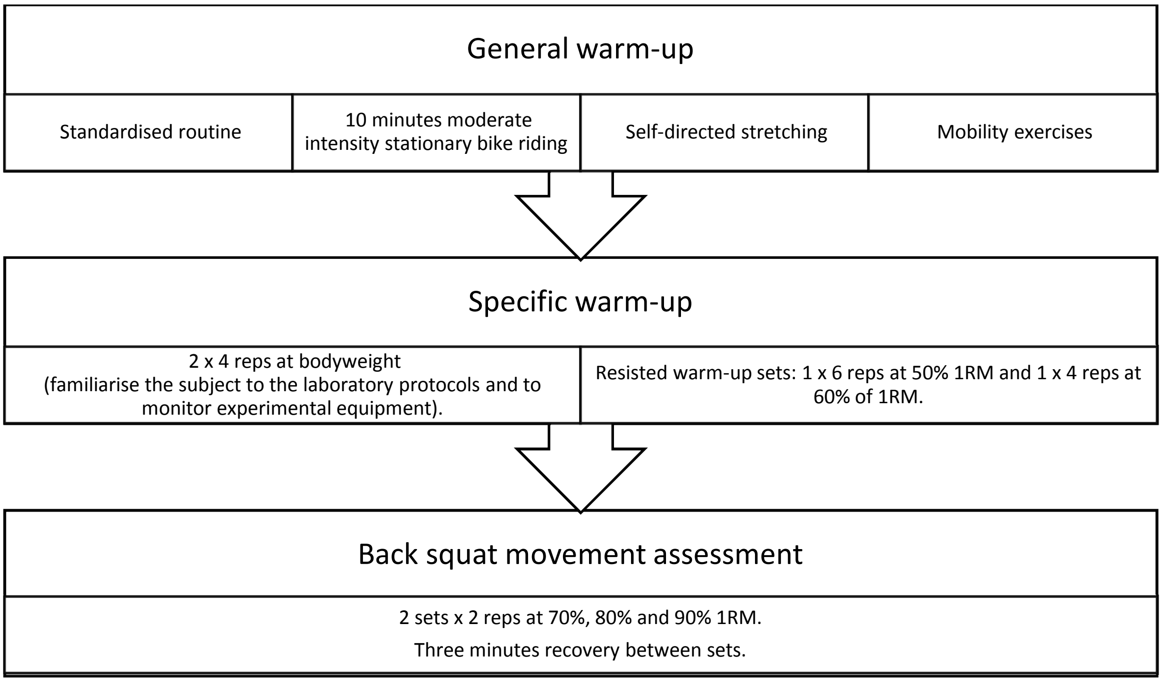

Figure 5.2. Flow chart representation of subject testing session two.

Ground Reaction Force. Two in-ground tri-axial force plates (9290AD, Kistler Instruments, Winterthur, Switzerland) were used to capture ground reaction force (GRF). During squat performance each foot was isolated on a separate force plate to permit assessment of the independent contribution of each leg to the movement, similar to previous protocols (233, 591). The analogue signal was captured at 1,000Hz using a data acquisition system (Vicon MX, Vicon, Oxford, UK). Signals from the force plates were filtered using a fourth order, low-pass Butterworth digital filter with a cut off frequency of 50 Hz. Calculation of key kinetic variables were performed for both left and right legs. Peak concentric GRF was the maximum value through the repetition. This was determined for either leg and the maximum value of the left and right summed at each time point during the concentric phase. The dominant leg was defined as that which produced the greater GRF each trial. The integration of force-time data (trapezoid method) was used to determine total concentric impulse (176, 294).

Three-Dimensional Motion Analysis. During all squat trials, a 10-camera digital optical motion analysis system (Vicon MX, Vicon, Oxford, UK) was used to record whole body three-dimensional movement patterns at 250Hz. A previously validated, whole-body model was used to capture and analyse movement patterns using Nexus software (Nexus 1.0) (152). The model uses a defined, 37 retro-reflective marker set and series of subject measurements to examine three-dimensional joint kinematics. An area of approximately 25 square meters surrounding the two force plates to a height of approximately three meters was calibrated using a wand calibration according to the manufacturers procedures (538). Force and kinematic data were captured simultaneously and a fifth-order spline interpolation applied to up-sample the motion analysis data to 1,000Hz. All trials were processed according to previous standards with Vicon Nexus 2.3 software using a customised pipeline incorporating a zero-lag fourth order 18Hz low pass Butterworth filter (515). All data was analysed using customised calculations in Microsoft Excel 2013.

Temporal Phase Definitions. The eccentric phase was defined by a 5% reduction in bilateral GRF (124), concluding at minimum marker displacement of the 7th cervical vertebra (C7). The concentric phase commenced from the end of the eccentric phase to maximum C7 displacement (129). The C7 marker has been demonstrated to be a reliable method of measuring barbell displacement (13).

Statistical Analysis. Within session reliability was calculated using intraclass correlation coefficient (ICC) and typical error expressed as a coefficient of variation (CV%) ±90% confidence limits (CL) (284) calculated using a customised Excel spreadsheet (286). The SWC% was calculated at 0.2 times the between-subject pure standard deviation (SD). For CV%, values below a threshold of 10% were deemed acceptable, a threshold often reported in many human performance reliability studies (19, 124, 143). A test was considered capable of detecting the SWC% if the CV% was less than the SWC% (455).

RESULTS

Reliability assessments of kinetic variables are presented in Table 5.2. Reliability was observed in peak and average concentric force. The CV% for GRF was very low (less than 4.0%) with very large to nearly perfect correlations across all loads of the squat (ICC range 0.87 – 0.97) (Table 5.2). Average and peak GRF measures were reliable for all loads for the squat (left leg, right leg, sum of left and right, dominant and non-dominant; CV% range = 1.1% - 4.6%). The combined left and right leg average GRF for the squat can be used to detect the SWC% (70% CV% 1.2< SWC% 2.3; 80% CV% 1.1 < SWC% 2.3; 90% CV% 1.4% < SWC% 2.1) (Table 5.3) with some measures of dominant and non-dominant (80% 1RM average GRF) suitable for detecting the SWC (80% D CV% 2.2 < SWC% 2.4; ND CV% 2.0 < SWC% 2.2)

(Table 5.4). The ICC for combined left and right legs was 0.95 or higher for peak and average GRF (Table 5.2 and 5.3). Measures of total concentric impulse also proved reliable across all intensities (CV = 6.4-10.3%; ICC = 0.71-0.89) (Table 5.5). The success rate across all loads of an average minimum depth of 90° was 86%.

Table 5.2. Reliability of peak concentric phase ground reaction force for the summed left and right legs (L&R), the left leg only (L) and right leg only (R).

Load	Leg	Mean of peak concentric GRF (SD)	CV% (CL)	ICC (CL)	SWC%
70%	L&R	3,216 (442)	2.9 (2.4-3.8)	0.96 (0.92-0.98)	2.7
	Left	1,596 (211)	3.7 (3.0-4.7)	0.94 (0.87-0.97)	2.6
	Right	1,637 (245)	3.9 (3.2-5.1)	0.94 (0.89-0.97)	2.9
80%	L&R	3,505 (468)	2.5 (2.1-3.3)	0.97 (0.94-0.99)	2.7
	Left	1,720 (212)	3.7 (3.1-4.7)	0.93 (0.86-0.97)	2.4
	Right	1,805 (255)	3.8 (3.2-5.0)	0.94 (0.88-0.97)	2.7
90%	L&R	3,693 (451)	2.4 (2.0-3.1)	0.97 (0.94-0.99)	2.4
	Left	1,827 (215)	4.6 (3.8-6.1)	0.87 (0.76-0.94)	2.2
	Right	1,877 (255)	3.4 (2.8-4.4)	0.95 (0.90-0.98)	2.6

Data presented as mean ± SD for all variables. **GRF**: ground reaction force; **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD.

Table 5.3. Reliability of average concentric phase ground reaction force for the summed left and right legs (L&R), the left leg only (L) and right leg only (R).

Load	Leg	Mean of average concentric GRF (SD)	CV% (CL)	ICC (CL)	SWC%
70%	L&R	2,390 (278)	1.2 (1.0-1.5)	0.99 (0.98-0.99)	2.3
	Left	1,179 (135)	3.3 (2.7-4.3)	0.93 (0.86-0.97)	2.2
	Right	1,211 (159)	3.2 (2.7-4.2)	0.95 (0.90-0.98)	2.5
80%	L&R	2,587 (303)	1.1 (0.9-1.4)	0.99 (0.98-1.00)	2.3
	Left	1,267 (136)	3.1 (2.6-4.1)	0.93 (0.86-0.97)	2.0
	Right	1,321 (177)	3.2 (2.7-4.1)	0.95 (0.91-0.98)	2.6
90%	L&R	2,753 (301)	1.4(1.1-1.8)	0.99 (0.97-0.99)	2.1
	Left	1,359 (139)	3.2 (2.7-4.2)	0.91 (0.83-0.96)	1.9
	Right	1,394 (173)	3.1 (2.6-4.1)	0.95 (0.89-0.98)	2.4

Data presented as mean ± SD for all variables. **GRF**: ground reaction force; **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD.

Table 5.4. Reliability of peak and average concentric phase ground reaction force by dominant (D) and non-dominant (ND).

Peak or Average GRF	Load	Leg	Mean of average concentric GRF (SD)	CV% (CL)	ICC (CL)	SWC%
Peak	70%	D	1,666 (239)	3.3 (2.8-4.3)	0.95 (0.91-0.98)	2.8
		ND	1,567 (208)	3.5 (2.8-4.5)	0.94 (0.89-0.98)	2.6
	80%	D	1,818 (247)	3.2 (2.7-4.2)	0.95 (0.91-0.98)	2.6
		ND	1,707 (215)	2.9 (2.4-3.7)	0.96 (0.92-0.98)	2.5
	90%	D	1,911 (246)	3.1 (2.6-4.1)	0.95 (0.90-0.98)	2.5
		ND	1,792 (211)	3.8 (3.1-5.0)	0.91 (0.83-0.96)	2.3
Average	70%	D	1,237 (149)	2.3 (1.9-2.9)	0.97 (0.94-0.99)	2.4
		ND	1,153 (134)	2.3 (1.9-3.0)	0.97 (0.93-0.99)	2.2
	80%	D	1,333 (166)	2.2 (1.8-2.9)	0.97 (0.95-0.99)	2.4
		ND	1,254 (143)	2.0 (1.7-2.6)	0.97 (0.95-0.99)	2.2
	90%	D	1,412 (158)	2.8 (2.3-3.6)	0.95 (0.89-0.98)	2.1
		ND	1,341 (150)	3.1 (2.6-4.1)	0.93 (0.87-0.97)	2.1

Data presented as mean ± SD for all variables. **GRF**: ground reaction force; **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD; **D**: dominant limb, producing the highest GRF during the trial; **ND**: non-dominant limb, producing the lowest GRF during the trial.

Table 5.5. Reliability of total concentric impulse for left and right legs (L&R), the left leg only (L) and right leg only (R).

	Load	Leg	Mean concentric impulse (SD)	CV% (CL)	ICC (CL)	SWC%
Total concentric impulse (Ns)	70%	L&R	2,072 (381)	8.0 (6.6-10.5)	0.83 (0.69-0.92)	3.2
		Left	1,022 (178)	7.9 (6.5-10.4)	0.82 (0.67-0.92)	3.1
		Right	1,050 (210)	9.3 (7.6-12.1)	0.81 (0.66-0.91)	3.5
	80%	L&R	2,578 (509)	6.4 (5.3-8.3)	0.89 (0.80-0.95)	3.4
		Left	1,262 (234)	6.5 (5.4-8.4)	0.88 (0.78-0.95)	3.2
		Right	1,317 (281)	7.6 (6.4-10.0)	0.87 (0.75-0.94)	3.5
	90%	L&R	3,245 (524)	9.1 (7.5-12.3)	0.74 (0.54-0.88)	2.8
		Left	1,632 (320)	9.4 (7.7-12.5)	0.78 (0.61-0.90)	3.2
		Right	1,672 (340)	10.5 (8.6-14.0)	0.76 (0.57-0.89)	3.3

Data presented as mean ± SD for all variables. **Impulse**: integration of force-time data (trapezoid method) during concentric phase; **SD**: standard deviation; **CV%**: coefficient of variation; **CL**: 90% confidence limits; **ICC**: intraclass correlation; **SWC%**: 0.2 times the between-subject pure SD.

DISCUSSION

Reliability is typically established between-sessions to assist coaches determine meaningful changes in performance over time (124). The current experimental design explicitly sought to determine the within-session reliability of multiple maximal intensity efforts of well-trained subjects (Table 5.1), characteristic of a resistance training session, on the premise that reliability would facilitate more rigorous data collection for coaches working with large athlete numbers. Measures of peak and average GRF for either leg individually, or summed, demonstrated acceptable levels of reliability during concentric squat performance at high relative loads in well-trained subjects. Furthermore, measures of total concentric impulse were reliable. However, despite acceptable reliability, the combination of left and right average GRF was able to detect the SWC with only two individual limb measures of GRF (80% 1RM average D and ND) suitable for detecting the SWC (CV% > SWC). These findings suggest coaches may confidently capture repeated maximal effort squat repetitions during sets with three minutes rest, typical of the training environment of well-trained athletes.

Reliability in sport science is assessed by a combination of absolute (CV%) and relative (ICC) consistency of measurement (519). A value of 10% has been utilised as an acceptable threshold for CV% and 0.80 for ICC (133). Comparable squat kinetic reliability has been reported in heavy squats or weighted squat jumps of 60% 1RM or greater, in a variety of subjects (ICC values above 0.80) (200, 457, 536). Further, the summed bilateral average GRF in the current investigation can be used to detect the SWC. A unique feature of this investigation is bilateral GRF assessment. The results of this study are that reliable detection of individual left and right, or dominant and non-dominant squat peak and average GRF is possible. Independent GRF assessment in heavy squats may be beneficial in detecting a meaningful change in performance due to training. With increasing accessibility to bilateral force plates, these findings may permit practitioners to capture individual GRF during repeated heavy squat performance.

As a product of GRF and time, impulse is an important determinant of athletic performance (142, 567). It is a critical measure as it determines the resulting velocity of movement as explained by the impulse-momentum relationship where changes in velocity are a result of the time course of force applied. In resistance training, as the mass during the repetition remains constant and the magnitude of duration is inherently limited by range of motion, impulse determines velocity, thus a larger impulse will produce a larger velocity (486). Thus, barbell velocity as measured in velocity-based training, is assessing a kinematic representation, or result, of impulse. Although reliable, total concentric impulse CV% measures were unable to detect the SWC. The reliability of impulse has primarily focussed on jump performances. Stalbom et al (2007) reported acceptable reliability in vertical impulse in 20cm single leg drop jumps (CV%=8.3; ICC=0.84) (519). This is an important finding confirming total concentric impulse as a reliable variable that may be used to greater understand squat performance at relatively heavy load ranges aimed at improving athletic movement.

Advances in force plate technology are enabling the assessment of exercise performance in the training environment. However, widespread data capture may be impractical with high athlete to technology ratios and the perception to test early in the session whilst fatigue is lower rendering data from later training sets less useful from a monitoring perspective. However, the results of this investigation suggest that the performance of six sets of two repetitions of 70-90% 1RM can be reliably performed by well-trained athletes. This may increase the capacity to capture important kinetic data in the practical setting by not limiting assessment to the first few fatigue free sets. Practically, provided sufficient rest prior to the testing set, coaches could rotate large numbers of training athletes through a testing station effectively capturing data with minimal disruption to training.

The homogenous subjects, and low subject numbers in the study limit the widespread application of the results to less experienced, or lower loaded squats and coaches working with different populations are encouraged to determine their specific reliability. As such, it may be difficult to generalise the findings of this homogenous population to lessor trained subjects or other bilateral resistance exercises. However, with accessibility to dual force plates increasing, future studies could be directed towards expanding the heterogeneity of the subjects, and the loads used. Furthermore, other kinetic variables other than peak and average GRF and impulse should be investigated. Future research should also involve investigation of other variables of bilateral assessment, the variability of bilateral kinetics to training interventions, less experienced subjects and between-session reliability.

In conclusion, the high reliability in GRF and total concentric impulse presented in this investigation demonstrates the ability for highly trained subjects to consistently perform repeatable maximal efforts in squats with large external loads. This reliability enables coaches a greater opportunity to capture kinetic data that may guide training program refinement.

PRACTICAL APPLICATIONS

This study suggests that S&C coaches working with large groups of well-trained athletes can confidently capture kinetics during multiple sets of high intensity squat. In particular, summed left and right leg GRF during the performance of the concentric phase, greater than 1.7% may represent a meaningful difference. Whilst not being able to identify the SWC, measures of asymmetry were reliable. Furthermore, total concentric impulse in weighted squats is reliable and represents the underlying capacity to generate momentum and bar velocity. Further research is required to determine if total concentric impulse may be used to monitor training performance and adaptation to training.

Acknowledgments

The authors would like to thank the subjects of the investigation for their commitment and dedication study. The authors would also like to thank Dr Prue Cormie for her contribution to the manuscript. The authors would also like to extend thanks to Dr Mervyn Travers for his assistance with the preparation of this manuscript. The Centre for Exercise and Sports Science Research (CESSR) at Edith Cowan University provided financial assistance and access to testing equipment. No further additional funding was sourced. The results of the present study do not constitute endorsement of the product by the authors or the Journal.

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