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Sources of Variability in Iso-Inertial Jump Assessments

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Purpose: This investigation aimed to quantify the typical variation for kinetic and kinematic variables measured during loaded jump squats. ***Methods:*** Thirteen professional athletes performed six maximal effort countermovement jumps on four occasions. Testing occurred over 2 d, twice per day (8 AM and 2 PM) separated by 7 d, with the same procedures replicated on each occasion. Jump height, peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), and peak rate of force development (RFD) measurements were obtained from a linear optical encoder attached to a 40 kg barbell. ***Results:*** A diurnal variation in performance was observed with afternoon values displaying an average increase of 1.5–5.6% for PP, RPP, MP, PV, PF, and MF when compared with morning values (effect sizes ranging from 0.2–0.5). Day to day reliability was estimated by comparing the morning trials (AM reliability) and the afternoon trials (PM reliability). In both AM and PM conditions, all variables except RFD demonstrated coefficients of variations ranging between 0.8–6.2%. However, for a number of variables (RPP, MP, PV and height), AM reliability was substantially better than PM. PF and MF were the only variables to exhibit a coefficient of variation less than the smallest worthwhile change in both conditions. ***Discussion:*** Results suggest that power output and associated variables exhibit a diurnal rhythm, with improved performance in the afternoon. Morning testing may be preferable when practitioners are seeking to conduct regular monitoring of an athlete's performance due to smaller variability.

Keywords: reliability, smallest worthwhile change, athlete monitoring, diurnal variation, power, training readiness

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The measurement of kinetic and kinematic variables during instrumented vertical jumps are commonly used to examine training effects after various short-term interventions[1,2] and, more recently, to gain insight into an athlete's state of neuromuscular fatigue via monitoring of performance during intensified training or competition.[3–5] In the regular training environment, especially in high performance sport where training loads are characteristically high, such tests may be useful for coaches and support staff by providing an objective method to assess an athlete's response to training and their recovery between sessions or competitions. However, in order to make informed decisions regarding changes in performance, it is critical that the typical variation or repeatability of the test be known. In this regard, the observation of meaningful changes in performance is reliant on knowing whether the observed change is outside of the variation that can be expected to occur by chance, or due to normal variation in the outcome variable. It follows that the more reliable the measurement is, the easier it will be to quantify real changes in performance.[6,7]

To enable the estimation of such values, it is necessary to conduct a reliability study using test-retest procedures, where repeated measures are taken from a group of subjects over a time period that is similar to the planned duration between testing sessions.[7] While a number of authors have established acceptable reliability of loaded and unloaded jump squats and associated kinetic and kinematic variables, comprehensive analyses of variability in athletic populations is limited. Cronin et al[8] and Hori et al[9] have reported trial-to-trial reliability, analyzing the change in performance between two consecutive trials, using unloaded and loaded (40 kg) countermovement jumps (CMJ) respectively. Cronin et al[8] reported acceptable reliability for force related measures (mean force, peak force and time to peak force), using a linear position transducer (LPT) and a force plate with coefficient of variation (CV) values between 2.1 and 7.4%. Hori et al[9] also reported acceptable trial-to-trial reliability for peak velocity, peak force, peak power and mean power using a variety of measurement devices (LPT, force plate and LPT + force plate), with CVs ranging from 1.2 to 11.1%. Sheppard et al[10] and Cormack et al[11] have evaluated the short-term (week-to-week) reproducibility of the CMJ and reported acceptable reliability for a range of variables, with CV values between 2.8 to 9.5%. These studies have presented reliability statistics based on either a single CMJ trial repeated one week apart,[11] or three single trials performed seven days apart, where the best trial from each testing session was used in the analysis.[10] While previous work has provided useful information to practitioners in regard to equipment and dependent variable selection, a comprehensive understanding of the typical variation of each of the variables available during instrumented jumps, and the appropriate testing methodologies, requires further investigation.

Cormack et al[11] have been the only researchers to consider the reliability statistics in relation to what is considered the smallest worthwhile effect on performance. The smallest worthwhile change (SWC), which is analogous to the minimum clinically important difference in the clinical sciences, is described as the smallest effect or change in performance that is considered practically meaningful.[12] For tests or measurements of athletic performance to be useful in detecting the SWC, the error associated with the measurement needs to be minimal, and ideally less than the SWC.[13] Hence for the valid interpretation of reliability outcomes, an in-depth analysis of typical variation needs to take into account the relationship between the typical variation of a measurement and the smallest effect that is considered important, or practically meaningful. Previous research has not addressed this in relation to kinetic and kinematic variables measured via instrumented jumps.

The final consideration is differences between measurements performed on the same day. It has been previously shown that a diurnal variation in maximal neuromuscular performance exists, with findings generally exhibiting morning nadirs and afternoon maximum values[14–19] indicating that neuromuscular capabilities are influenced by time of day. While authors have typically ensured that time of day was standardized within subjects, the potential differences in typical variation when testing is conducted at differing times of day has not been examined (ie, time of day was generally not standardized between subjects). Hence, along with examining time of day differences in neuromuscular performance, it may also be appropriate to examine loaded CMJs for differences in variability, or reproducibility, between morning and afternoon testing sessions. The present study aimed to (i) evaluate the time of day effect on jump performance and associated kinetic and kinematic variables, (ii) to comprehensively evaluate the reproducibility/variability in performance of highly trained athletes familiar with the testing procedures and (iii) to establish which variables are useful in detecting the smallest worthwhile change in performance.

Methods

Design

To examine the effect of time of day on jump performance, subjects performed six loaded CMJs in the morning (AM; 0800–0900) and afternoon (PM; 1400–1500) after a standardized warm-up. Based on pilot testing, the six jumps were divided into two sets of three, where athletes rested for 2–3 min between sets, to avoid any fatiguing effects across consecutive jumps. Differences in performance between AM and PM sessions were compared using within-subject statistical procedures. All subjects repeated the same procedures 7 d later, to examine differences in intersession reliability between testing conditions (AM and PM).

Subjects

Thirteen professional male rugby union players (mean ± SD: age 23.7 ± 2.7 y, height 1.86 ± 0.10 m, weight 103.8 ± 10.7 kg) participated in this study as part of their regular preseason training regime. All subjects were free from injury and were highly familiar with the performance test requirements. Written informed consent was obtained from all participants and testing procedures were approved by the Australian Institute of Sport ethics committee.

Procedures

Before each testing session subjects performed a 10 min dynamic warm-up consisting of general whole body movements emphasizing an increase in range of movement, a variety of running patterns and four sets of three practice jumps. Subjects were required to progressively increase the intensity of the exercises until the end of the warm-up period until they felt they were capable of maximal performance.

Jump assessments consisted of each subject performing a CMJ with a load of 20 kg on an Olympic lifting bar (ie, total load of 40 kg), a protocol that has been used extensively with this, and similar populations. The subject stood erect with the bar positioned across his shoulders and was instructed to jump for maximal height while keeping constant downward pressure on the barbell to prevent the bar moving independently of the body. Each subject performed three repetitions, pausing for approx. 3–5 s between each jump. Subjects then rested for 2–3 min before repeating a second set of three jumps. No attempts were made to standardize the starting position, amplitude, or rate of the countermovement. A displacement-time curve for each jump was obtained by attaching a digital optical encoder via a cable (GymAware Power Tool. Kinetic Performance Technologies, Canberra, Australia) to one side of the barbell. This system recorded displacement-time data using a signal driven sampling scheme[20] where position points were time-stamped when a change in position was detected, with time between samples limited to a minimum of 20 ms. The first and second derivate of position with respect to time was taken to calculate instantaneous velocity and acceleration respectively. Acceleration values were multiplied by the system mass to calculate force, and the given force curve multiplied by the velocity curve to determine power. Mean values for force (mean force; MF) and power (mean power; MP) were calculated over the concentric portion of the movement and peak values for velocity (peak velocity; PV), force (peak force; PF) power (peak power; PP) and relative power (relative peak power; RPP) were also derived from each of the curves. Jump height was determined as the highest point on the displacement-time curve.

Statistical Analysis

Means and standard deviations (SD) were computed for the kinetic and kinematic variables in the AM and PM conditions for Weeks 1 and 2 independently. Thereafter intraday analyses examining the diurnal effect were conducted using the mean values of six trials from the AM and PM sessions by averaging Weeks 1 and 2 (mean diurnal response). To examine the AM to PM differences in performance, effects were calculated as the mean difference divided by the pooled between-subject SD, and were characterized for their practical significance using the criteria suggested by Rhea[21] for highly trained participants as follows: <0.25 = trivial, 0.25–0.50 = small, 0.51–1.0 = moderate, and >1.0 = large. In addition, a substantial performance change was accepted when there was more than a 75% likelihood that the true value of the standardized mean difference was greater than the smallest worthwhile (substantial) effect.[22] Thresholds for assigning the qualitative terms to chances of substantial effects were: <1%, almost certainly not; <5%, very unlikely; <25% unlikely; 25–75%, possibly; >75% likely; >95% very likely; and >99% almost certain. The smallest worthwhile effect on performance or SWC from test to test was established as a "small" effect size (0.25 × between-participant SD) according to methods outlined previously.[7]

When investigating reliability Hopkins[7] has recommended that the systematic change in the mean, as well as measures of absolute and relative consistency (ie, within-subject variation and retest correlations respectively) be reported. Systematic changes in the mean from AM to AM and PM to PM were examined via the procedures described above for examining the diurnal response. The absolute reliability or typical within-subject variation was quantified via the CV (%). For trial-to-trial reliability this was calculated as $\sqrt{(\sum SD^2/n)}$, where SD equals the standard deviation for each individual across the six trials, and n is the number of subjects. This value was then divided by $\sqrt{6}$ to give the estimated error in the mean of six trials, which represents the variation in the mean if the six trials were to be repeated without any intervening effects. The AM to PM reliability, calculated as the mean change in AM to PM performance on the same day, was quantified as the SD of the change scores divided by $\sqrt{2}$. Week-to-week reliability was calculated using the same formula, based on the change scores from Week 1 to Week 2 for the two morning trials (AM reliability) and then the two afternoon trials (PM reliability). To examine the influence of the number of trials on the reliability outcomes, we calculated the week-to-week CV using the first trial from Week 1 and Week 2, the mean of trial 1 and 2, the mean of trials 1–3, the mean of trials 1–4 and so on.

Results

Performance characteristics across the AM and PM sessions are presented in Table 1. No substantial systematic change was observed in any variable across the six trials, indicating that learning effects and fatigue did not affect the results within each session. Figure 1 illustrates the mean changes for the AM-PM trials, AM-AM trials, and the PM-PM trials. Small to moderate time of day effects were observed for PP, RPP, MP, PV, PF and jump height, with a mean diurnal response of 4.3–6.1% (Figure 1A). No substantial changes in the mean were observed from week to week in either the AM or PM conditions (Figure 1B and 1C).

Reliability estimates based on the variation within a single session, between sessions within the same day (AM to PM), and from week-to-week are presented in Table 2. Trial-to-trial reliability was good for all variables (range = 1.4–7.7%)

Table 1 Mean ± SD for kinetic and kinematic variables measured during 40 kg CMJ. Results were calculated using the mean of six trials during each session and averaged for Week 1 and Week 2.

Variable	AM	PM
Peak Power (W)	5457 ± 453	5719 ± 424
RPP (W/kg)	53.1 ±7.8	55.8 ± 8.4
Mean Power (W)	2347 ± 225	2451 ± 189
Peak Velocity (m/s)	2.53 ± 0.17	2.60 ± 0.19
Peak Force (N)	3015 ± 375	3116 ± 363
Mean Force (N)	1435 ± 105	1433 ± 111
Jump Height (cm)	28.9 ± 3.7	30.2 ± 5.5
RFD (kN/s)	20.9 ± 7.7	21.7 ± 8.0

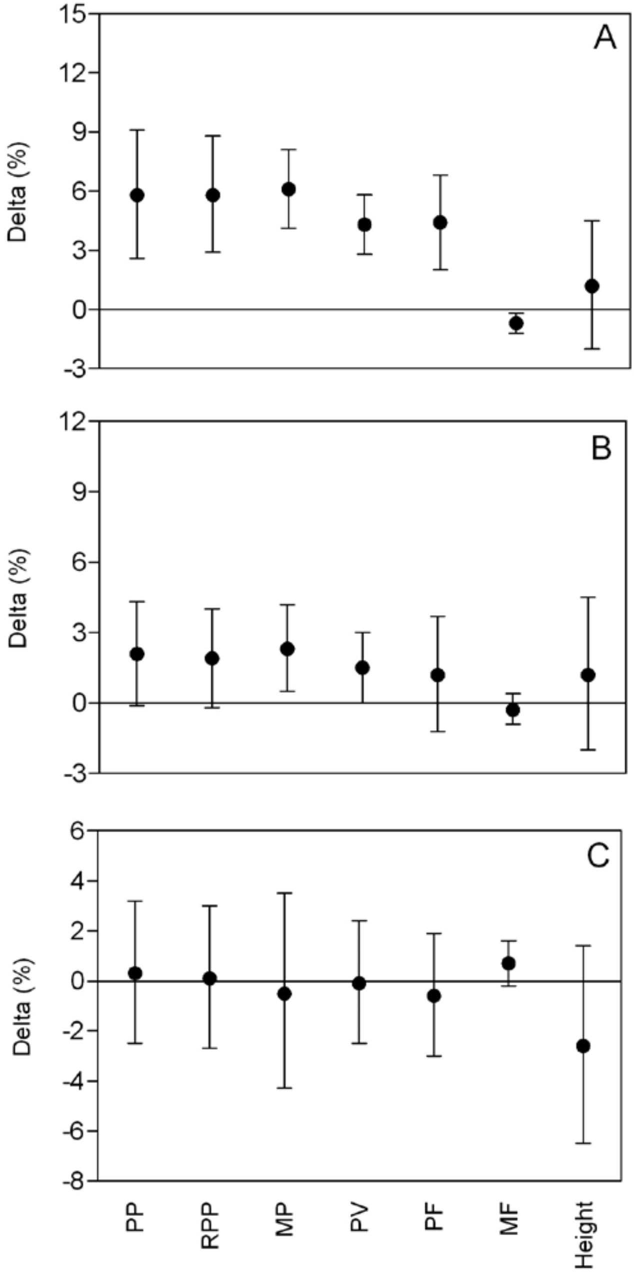

Figure 1 — Mean changes in performance ± 90% confidence limits for peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), jump height (Height). (A) mean change in performance from AM to PM (average of trials for week 1 and 2); (B) mean change in performance from week 1 to week 2 for AM trials; (C) mean change in performance from week 1 to week 2 for PM trials.

Table 2 Coefficients of variation (CV) representing the expected variation from trial-to-trial; for the mean of six trials within a session; between AM and PM sessions; and for the mean of six trials between sessions conducted 1 wk apart. Smallest worthwhile change (SWC) values are also presented for comparisons with the estimates of typical variation.

	Trial-to-trial CV (%) within a session		CV (%) of the mean of the six trials			Week-to-Week CV (%)		
Variable	AM	PM	AM	PM	Within-day CV (%)	AM	PM	SWC (%)
Peak Power	5.5	5.2	2.3	2.1	3.4	2.5	3.4	2.4
RPP	5.6	5.2	2.3	2.1	3.4	2.4	3.4	3.9
Mean Power	5.3	5.0	2.2	2.0	2.9	2.1	4.7	2.5
Peak Velocity	2.6	2.8	1.1	1.1	2.3	1.7	2.9	1.9
Peak Force	5.5	5.3	2.2	2.2	2.7	2.9	2.9	3.2
Mean Force	1.5	1.4	0.6	0.6	0.8	0.8	1.0	1.9
Height	7.0	7.7	2.9	3.2	6.6	4.3	6.2	4.3
RFD	39.4	32.5	16.1	13.3	15.5	22.5	25.9	10.8

except RFD. The reliability based on the mean of six trials was very high, with CVs less than 3.2% for all variables except RFD (13.3–16.6%). In addition to exhibiting excellent absolute reliability, PP, RPP, MP, PV, PF and height yielded typical variation scores less than the SWC.

When the mean of the six trials were used to examine week-to-week test-retest reliability a similar pattern emerged with all variables except RFD exhibiting high reliability coefficients (range = 0.8–6.2%). Only height in the PM condition had a CV exceeding 5%. However, while such values would generally be considered to represent excellent reliability, PP, PF and MF were the only variables where the typical variation was less than the SWC in both conditions. A number of variables (RPP, MP, PV and height) demonstrated CV < SWC in the AM condition only.

Along with changes in AM and PM performance, substantial differences in reliability were observed for a number of variables across the AM and PM conditions (Table 2). Based on the analysis, it is likely to very likely (ie, > 75% likelihood) that the week-to-week variability in the PM sessions was greater than the variability in the AM sessions for RRP, MP and PV. It was unclear if there were substantial differences in variability between AM and PM for all other variables.

Figure 2 illustrates the differences in AM and PM reliability, along with differences in the estimated typical variation as the number of trials included in the analysis increased. For PP, RPP, MP and PV it is evident that PM variability is greater than AM variability, and as the number of trials included in the analysis was increased, the typical week-to-week variation was reduced. A contrasting result was observed for PF with AM variability greater than PM variability. In addition the low variability achieved for PF in the PM session was not noticeably reduced as more trials were included. For MF, which demonstrated the lowest variability in all analyses, AM and PM reliability was similar, and both varied very little with the inclusion of additional trials. Similarly the variability for height between the two PM sessions was minimally reduced when a single trial was compared with the mean of 6 trials (6.2% and 4.8% respectively). RFD displayed trends similar to PP, RPP, MP and PV (ie, greater PM variability and greater reliability with increased trials); however, the CVs are greater than what can be considered of practical value (range = 23 to 37%).

Discussion

To confidently estimate true maximal athletic capacities, and assess real and meaningful changes in performance a greater understanding of how variables are expected to vary both within and between testing sessions is needed. Authors have often reported acceptable reliability for force and power related variables during CMJs, with within-subject variability coefficients ranging from 1.2 to 11.1%.[8–11,23] Our findings were similar for a number of variables, with all variables except RFD producing CVs between 0.8 and 6.2%, for trial-to-trial and week-to-week reliability. The novelty of our statistical analysis demonstrates that the variability associated with the time of day that testing is performed affects the extent of variation inherent in performance. In addition we have shown that while most variables demonstrated "acceptable" reliability, the relationship between the CV and the SWC signifies that limited variables are capable of detecting practically important changes in performance.

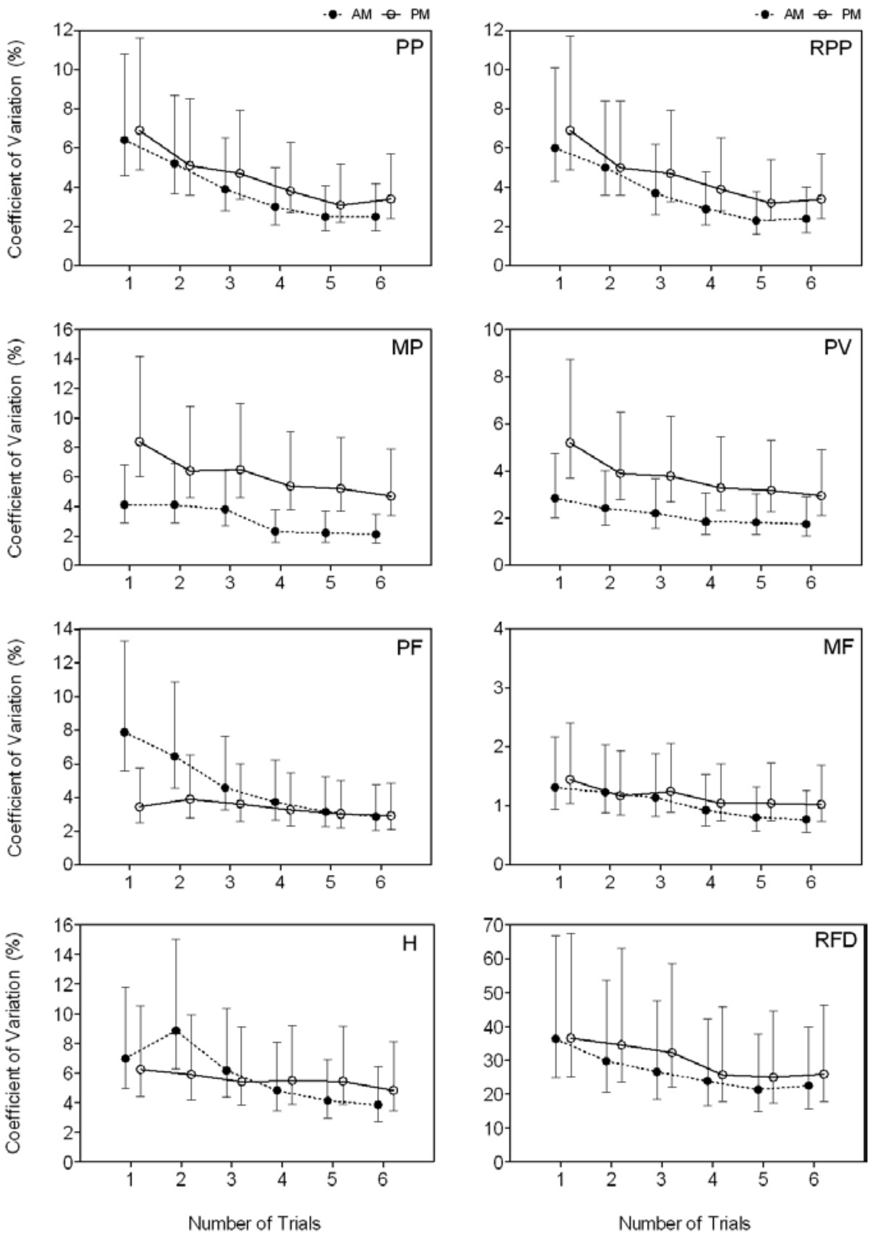

Figure 2 — Mean coefficients of variation ± 90% confidence limits of for peak power (PP), relative peak power (RPP), mean power (MP), peak velocity (PV), peak force (PF), mean force (MF), jump height (H) and peak rate of force development (RFD) based on the time of day (AM or PM) and the number of trials performed.

It is important to recognize that while both trial-to-trial and short-term (week-to-week) reliability are important, in the context of athletic assessment they serve different purposes. The error estimate associated with trial-to-trial reliability can be attributed to random measurement error, as there is little scope for biological changes.[7] This value assists the practitioner in estimating the amount of error likely to occur around a single measurement within a single session, thus allowing for an accurate estimation of the true likely range of the outcome variable. Our results indicate that if a single trial protocol is used, the practitioner can expect an approximate 4-8% error for most kinetic and kinematic variables (the error associated with MF was lower at approx. 1.5%, while RFD demonstrated considerably greater random error, ranging from 32 to 40%). When a six-trial protocol was used, the error rate was reduced for all variables, and the variability from trial-to-trial was estimated between 1.1–3.2%; RFD, however, still remained high at approx. 13–16%. Thus the inclusion of six trials in the analysis demonstrated the error associated with each trial was approx. 1–3%, which is similar to the 2–3% reported by Cronin et al[8] but substantially less than Hori et al[9] who reported variations of 9.0–11.1% for PF, PP and MP.

When the purpose of testing is to monitor an athlete's response to training and their recovery between sessions or weekly competitions, the focus is on the short-term variability. Such short-term variability includes the random measurement error plus associated "normal" or biological variation that occurs over time. This type of reliability is most commonly reported and is useful for estimating the magnitude of error associated with test-retest designs, where subjects are tested before and after an intervention, or when performance tests are used for regular athlete monitoring. Our results indicate that when testing was repeated 7 d later, additional biological error was present for all variables. For example, PP demonstrated a typical trial-to-trial error of approx. 2%, which increased to approx. 3.5% when week-to-week variability was included. While no previous studies have examined week-to-week reliability using similar instrumentation, the range of 0.8–6.2% would satisfy the criteria for acceptable reliability reported in the literature.

Although there is no preset standard for acceptable CV values, many researchers have set a criteria of <10% for "good" reliability.[6,10,11] Upon meeting this requirement, authors have generally recommended that their test protocols can be used to confidently assess changes in a range of neuromuscular parameters. However, knowing that a change is "real" (ie, outside of the expected measurement error), does not provide the practitioner with information regarding the meaningfulness of the change. To identify meaningful or worthwhile changes in performance, knowledge of the SWC is needed.[12] It has been suggested that if the typical variation (CV) of a test or variable is less than the SWC, then the test/variable is rated as "good," while a variable with a CV that is considerably greater than the SWC would signify marginal practicality of that variable.[13] Previously, only Cormack et al[11] compared their reported reliability estimates to what was considered the SWC in performance, and while they reported CVs less than their criterion of 10% for a large number of variables, only MF had a typical variation less than the SWC. In our analysis, only MF and PF demonstrated CV < SWC in both AM and PM conditions. While all variables other than RFD easily met the normally accepted criterion of <10%, they were generally not capable of detecting the SWC. Exceptions to this included the AM reliability values for RPP (CV = 2.4%; SWC = 3.9%), MP (CV = 2.1%; SWC = 2.5%) and PV (CV = 1.7%; SWC = 1.9%). Therefore, when implementing a testing program to monitor changes in neuromuscular performance characteristics, our results suggest that MF and PF would be the most useful variables to monitor. However, confounding issues remain, since it is possible that the most reliable tests are not necessarily the most effective for monitoring performance in athletes.[24] When using an assessment of neuromuscular performance to predict changes in performance readiness in team sports, or as an indicator of fatigue, it is important to also consider the relationship of the variable to successful performance. Although MF is very reliable, its stable nature may also mean that it is not able to effectively discriminate between positive and negative performance outcomes. While this is yet to be investigated, preliminary findings by the current authors suggest that even during periods of highly stressful training and competition, MF only tends to fluctuate by approximately 1%. In addition, previous research examining the relationship between kinetic and kinematic variables and dynamic strength tests[25] and sprint performance,[26] have not identified MF as an important predictor of successful performance. While MF was not included in these previous analyses, PP, MP and PF relative to body mass were reported to be strong predictors of performance.[25–28] Therefore researchers require the development of methods that allow for other variables that are more informative (ie, a stronger relationship to competitive performance) to be capable of detecting the SWC. This can only be achieved by reducing the typical variation associated with the practiced testing methodologies.

To investigate means for reducing the typical variation, we examined the effect of trial size on the week-to-week variability. Though it is well known that increasing the number of trials from which the reliability statistics are generated reduces the noise associated with the test, the number of trials before the error is reduced to an acceptable level is not well documented. Our results indicate that the inclusion of additional trials (up to six) improved the reliability of PP and RPP by 4–5%. The differences in reliability from the analysis of one to six trials were also practically significant for MP, PV and PF (approx. 1–4%). These findings suggest that the typical variation from week-to-week can be improved by using the average of six trials, rather than a single trial protocol. Numerous other studies have strongly suggested that multiple trial protocols are necessary for obtaining stable results in the assessment of lower limb function in a variety of activities.[29–31] For example, Rodano and Squadrone[30] reported that a 12 trial protocol was needed for establishing stable results for power outputs of the ankle, knee and hip joints during vertical jumping. James et al[31] indicated that a minimum of four and possibly as many as eight trials should be performed to achieve performance stability of selected ground reaction force variables during landing experiments. We capped the number of trials in our study at six (2 sets × 3 repetitions) as we considered this a viable number when using such a protocol as a weekly monitoring tool with a large squad of players. By using the average of additional trials, it may be possible to reduce the error further; however, it is felt such a protocol would have limited feasibility in the regular training environment of high performance athletes.

Interestingly we found that AM variability was lower than PM variability for a number of variables (Table 1), which has important implications when the magnitude of variability is compared with SWC. For RPP, MP, PV and height, greater variability in the PM sessions meant that they were rejected on the basis that the estimated typical error was greater than the signal we are interested in measuring (ie, CV > SWC). That is, while the CV < SWC in the AM condition, indicating that the variables were in fact capable of detecting worthwhile changes in performance, the

PM condition did not satisfy this criteria. Hence, since greater variability is present when testing was conducted in the afternoon, it appears that it may be more difficult to identify worthwhile changes in performance and therefore limit the utility of such assessments for monitoring training readiness and recovery between sessions.

Practical Applications

Practitioners seeking to conduct regular monitoring of an athlete's performance are recommended to standardize the time of day that assessments occur. If maximal performance is paramount, then afternoon testing is likely to produce better results. However, if monitoring small changes in performance, changes may be more confidently observed if testing occurs in the morning due to smaller week-to-week variability. The use of an optical-encoder to measure a range of kinetic and kinematic variables during CMJs has been shown to be effective for monitoring practical changes in MF and PF, but less practical for monitoring small but meaningful changes in power, velocity and jump height. RFD was shown to be unreliable and cannot be used to confidently assess changes in neuromuscular status. Although MF and PF were the only variables to demonstrate CV less than the SWC, other variables with acceptable reliability may be more related to performance, or have greater sensitivity to change, and require further investigation. Increasing the number of trials included in the analysis is one way to reduce the typical variation in kinetic and kinematic variables and enhances their utility in monitoring small but practical changes in performance across a training week.

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References

1. Adams K, O'Shea J, O'Shea K, Climstein M. The effect of six weeks of squat, plyometric and squat-plyometric training on power production. *J Appl Sport Sci Res.* 1992;6:36–41.
2. McBride J, Tripplett-McBride T, Davie A, Newton R. The effect of heavy-vs. light-load jump squats on the development of strength, power, and speed. *J Strength Cond Res.* 2002;16:75–82.
3. Welsh T, Alemany J, Montain S, et al. Effects of intensified military field training in jumping performance. *Int J Sports Med.* 2008;29:45–52.
4. Cormack S, Newton R, McGuigan M. Neuromuscular and endocrine responses of elite players to an Australian Rules Football match. *Int J Sports Physiol Perform.* 2008;3:359–374.
5. Ronglan L, Raastad T, Borgeson A. Neuromuscular fatigue and recovery in elite female handball players. *Scand J Med Sci Sports.* 2006;16:267–273.
6. Atkinson G, Nevill A. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med.* 1998;26:217–238.
7. Hopkins W. Measures of reliability in sports medicine and science. *Sports Med.* 2000;30:1–15.
8. Cronin J, Hing R, McNair P. Reliability and validity of a linear position transducer for measuring jump performance. *J Strength Cond Res.* 2004;18:590–593.

9. Hori N, Newton R, Andrews W, Kawamori N, McGuigan M, Nosaka K. Comparison of four different methods to measure power output during the hang power clean and the weighted jump squat. *J Strength Cond Res*. 2007;21:314–320.
10. Sheppard J, Cormack S, Taylor K, McGuigan M, Newton R. Assessing the force-velocity characteristics of the leg extensors in well-trained athletes: The incremental load power profile. *J Strength Cond Res*. 2008;22:1320–1326.
11. Cormack S, Newton R, McGuigan M, Doyle T. Reliability of measures obtained during single and repeated countermovement jumps. *Int J Sports Physiol Perform*. 2008;3:131–144.
12. Hopkins W, Hawley J, Burke L. Design and analysis of research on sport performance enhancement. *Med Sci Sports Exerc*. 1999;31:472–485.
13. Pyne D. Interpreting the results of fitness testing. in *International Science and Football Symposium*. 2003: Victorian Institute of Sport.
14. Martin A, Carpentier A, Guissard N, van Hoecke J, Duchateau J. Effect of time of day on force variation in human muscle. *Muscle Nerve*. 1999;10:1380–1387.
15. Sedliak M, Finni T, Cheng S, Haikarainen T, Hakkinen K. Diurnal variation in maximal and submaximal strength, power and neural activation of leg extensors in men: Multiple sampling across two consecutive days. *Int J Sports Med*. 2008;29:217–224.
16. Coldwells A, Atkinson G, Reilly T. Sources of variation in back and leg dynamometry. *Ergonomics*. 1994;37:79–86.
17. Gauthier A, Davenne D, Martin A, Hoecke JV. Time of day effects on isometric and isokinetic torque developed during elbow flexion in humans. *Eur J Appl Physiol*. 2001;84:249–252.
18. Wyse J, Mercer T, Gleeson N. Time-of-day dependence of isokinetic leg strength and associated interday variability. *Br J Sports Med*. 1994;28:167–170.
19. Racinais S, Hue O, Blonc S. Time-of-day effects on anaerobic muscular power in a moderately warm environment. *Chronobiol Int*. 2004;21:485–495.
20. Qaisar S, Fesquet L, Renaudin M. Adaptive rate sampling and filtering based on level crossing sampling. *EURASIP Journal on Advances in Signal Processing*. 2009;7:1-12.
21. Rhea M. Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J Strength Cond Res*. 2004;18:918–920.
22. Hopkins W (2002) Probabilities of clinical or practical significance. *Sportscience* 6 sportsci.org/jour/0201/wghprob.htm.
23. Chiu L, Schilling B, Fry A, Weiss L. Measurement of resistance exercise force expression. *J Appl Biomech*. 2004;20:204–212.
24. Hopkins W, Schabort E, Hawley J. Reliability of power in physical performance tests. *Sports Med*. 2001;31:211–234.
25. Nuzzo J, McBride J, Cormie P, McCaulley G. Relationship between countermovement jump performance and multi-joint isometric and dynamic tests of strength. *J Strength Cond Res*. 2008;22:699–707.
26. Harris N, Cronin J, Hopkins W, Hansen K. Relationship between sprint times and the strength/power outputs of a machine squat jump. *J Strength Cond Res*. 2008;22:691–698.
27. Dowling J, Vamos L. Identification of kinetic and temporal factors related to vertical jump performance. *J Appl Biomech*. 1993;9:95–110.
28. Maulder P, Bradshaw E, Keogh J. Jump kinetic determinants of sprint acceleration performance from starting blocks in male sprinters. *J Sports Sci Med*. 2006;5:359–366.
29. Hamill J, McNiven S. Reliability of selected ground reaction force parameters during walking. *Hum Mov Sci*. 1990;9:117–131.
30. Rodano R, Squadrone R. Stability of selected lower limb joint kinetic parameters during vertical jump. *J Appl Biomech*. 2002;18:83–89.
31. James CR, Herman JA, Dufek JS, Bates BT. Number of trials necessary to achieve performance stability of selected ground reaction force variables during landing. *J Sports Sci Med*. 2007;6:126–134.