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Reliability of Performance Measurements Derived From Ground Reaction Force Data During Countermovement Jump and the Influence of Sampling Frequency

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[1]*School of Exercise, Biomedical and Health Sciences, Edith Cowan University, Joondalup, Western Australia, Australia;*
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Abstract

Hori, N, Newton, RU, Kawamori, N, McGuigan, MR, Kraemer, WJ, and Nosaka, K. Reliability of performance measurements derived from ground reaction force data during countermovement jump and the influence of sampling frequency. *J Strength Cond Res* 23(3): 874–882, 2009—Force platforms are used extensively to measure force and power output during countermovement jump (CMJ). The purpose of this study was to examine measurement reliability and validity of commonly used performance measurements derived from ground reaction force (GRF)–time data during CMJ and the influence of sampling at different frequencies. Twenty-four men performed 2 trials of CMJ on a force platform, and GRF-time data were sampled at a rate of 500 Hz. Data obtained at 500 Hz were considered as the reference, and then data were resampled at 400, 250, 200, 100, 50, and 25 Hz, using interpolation. Commonly used power, force, and velocity performance measures were obtained from GRF-time data. Reliability was assessed by intraclass correlation coefficient (ICC) and coefficient of variation (CV) between the 2 trials within the session. Peak power, peak force, and peak velocity were highly reliable across all sampling frequencies (ICC = 0.92–0.98, CV = 1.3–4.1). Percentage differences from 500-Hz reference values ranged from −0.85 to 0.20% at 400 Hz, −1.88 to 0.89% at 250 Hz, −1.80 to 1.31% at 200 Hz, −3.63 to 3.34% at 100 Hz, −11.37 to 6.51% at 50 Hz, and −13.17 to 9.03% at 25 Hz. In conclusion, peak power, force, and velocity measurements derived from GRF to assess leg extensor capabilities are reliable within a test session except for peak rate of force development and time to peak power. With regard to sampling frequency, scientists and practitioners may consider sampling as low as 200 Hz, depending on the purpose of measurement, because the percentage difference is not markedly enlarged until the frequency is 100 Hz or lower.

Key Words velocity, impulse, momentum, force platform, vertical jump

Introduction

For many sporting movements, the success of performance is largely affected by how much force and power is applied toward objects such as the ground, a ball, or sporting equipment (15). Thus, possessing the ability of the neuromuscular system to output high force and power and to increase them rapidly from a relatively relaxed muscle state is one of the most important goals for strength and conditioning programs (1). Such characteristics of the neuromuscular system have been termed "strength qualities" (14), and, for ground-based tasks (e.g., ball games, track and field) in which the leg extensors are predominant, an explosive movement of short duration such as vertical jump is often used to assess these qualities (11). In particular, countermovement jump (CMJ) is one of the most common test measurements among scientists and practitioners (3,8,9,18,19). A CMJ typically involves the athlete, keeping his or her hands on the hips or with an arm swing, squatting down to about 90° knee bend and then immediately jumping vertically as high as possible. By measuring force, velocity, and power output during CMJ, it is possible to distinguish athletes with high and low leg extensor abilities (23), examine the effects of a given training intervention (16,22), and/or monitor athletes' progress during their long-term training programs (1). Traditionally, only the jump height during CMJ has been used as the performance outcome. However, more recently, research has

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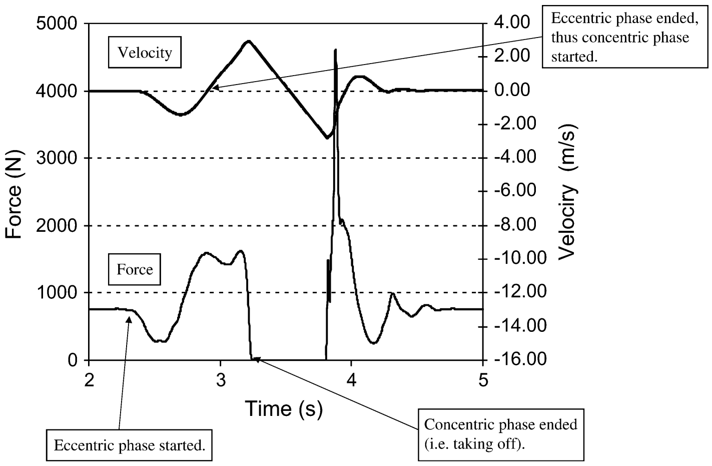

Figure 1. Definition of eccentric and concentric phases.

understand the underlying qualities contributing to the performance (14). However, to have confidence in the utility of these measurements for research and athlete monitoring, the reliability of measurement of the variables needs to be assessed in detail.

To measure force, velocity, and power output during CMJ, several different methodologies are available (6,12). For example, Wilson et al. (22) used displacement-time data obtained from a position transducer, Newton et al. (16) used ground reaction force (GRF)–time data obtained from a force platform, and Young et al. (23) used a combination of displacement-time data obtained from a position transducer and GRF-time data obtained from a force platform to calculate the performance values. Despite a variety of methodologies, it has been suggested that these variables, measured directly

indicated that it is instructive to examine a range of characteristics of how the athlete produces this jump height. In this process of strength diagnosis, scientists and practitioners examine these performance variables in an attempt to

Table 1. Reliability of measurements.

	Peak power		Mean power		Peak force		Mean force		Peak velocity	
	ICC	CV	ICC	CV	ICC	CV	ICC	CV	ICC	CV
500 Hz	0.98	2.3	0.84	7.8	0.92	4.1	0.93	3.9	0.98	1.3
400 Hz	0.98	2.3	0.84	8.3	0.92	4.1	0.93	4.0	0.98	1.3
250 Hz	0.98	2.3	0.77	8.9	0.92	4.1	0.90	4.4	0.98	1.3
200 Hz	0.98	2.3	0.85	7.4	0.92	4.1	0.94	3.7	0.98	1.3
100 Hz	0.97	2.7	0.82	7.9	0.92	4.1	0.92	3.9	0.98	1.3
50 Hz	0.98	2.6	0.74	9.8	0.92	4.1	0.88	5.0	0.98	1.3
25 Hz	0.96	3.3	0.71	12.3	0.93	3.9	0.84	6.3	0.95	1.7

	Minimum velocity		Peak RFD		Time to peak force		Average RPD		Time to peak power	
	ICC	CV	ICC	CV	ICC	CV	ICC	CV	ICC	CV
500 Hz	0.78	9.8	0.66	24.0	0.75	11.4	0.91	8.2	0.85	7.0
400 Hz	0.78	9.7	0.66	24.0	0.74	11.8	0.92	8.1	0.85	6.8
250 Hz	0.78	9.8	0.69	23.0	0.76	11.3	0.92	7.9	0.85	6.8
200 Hz	0.78	9.8	0.66	24.0	0.78	10.8	0.92	8.5	0.83	7.2
100 Hz	0.78	9.7	0.67	23.5	0.75	11.6	0.91	8.6	0.84	7.5
50 Hz	0.78	9.7	0.75	20.7	0.75	12.3	0.95	8.0	0.83	7.1
25 Hz	0.75	10.0	0.75	22.2	0.74	13.4	0.87	14.9	0.57	14.4

ICC = intraclass correlation coefficient; CV = coefficient of variation; RFD = rate of force development; RPD = rate of power development.

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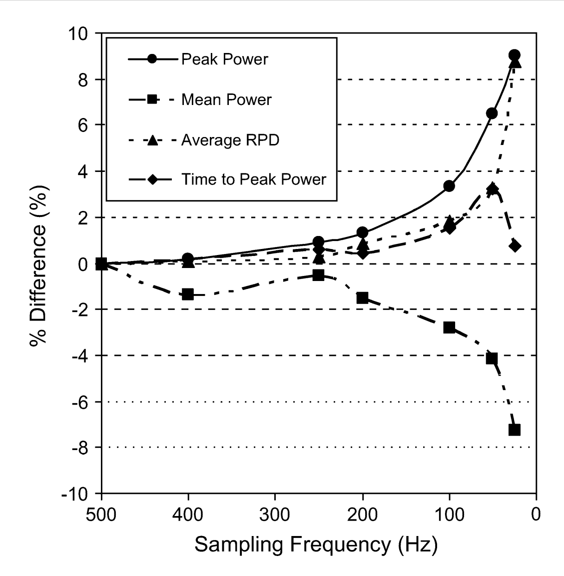

Figure 2. Percentage differences between power and related variables derived from the reference 500-Hz data and successively lower sample rates. RPD = rate of power development.

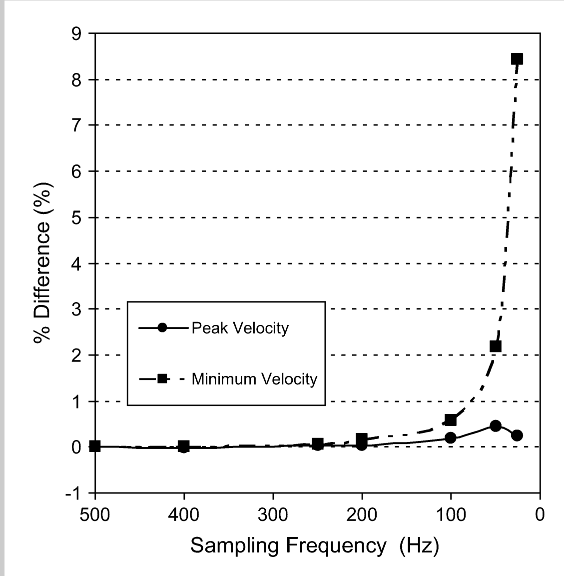

Figure 4. Percentage differences between velocity variables derived from the reference 500-Hz data and successively lower sample rates.

or calculated from GRF-time data recorded from a force platform, provide the most accurate way to assess strength qualities during a vertical jump (12).

In actual testing situations, force output needs to be measured throughout a certain period (i.e., at least from the beginning to the end of the movement) because the force output varies with time. During the data sampling, how often the signal is sampled each second is termed sampling frequency (13). In general, a force platform with a high capacity of sampling frequency is more expensive than one with low capacity. On the other hand, a force platform with high portability usually possesses lower capacity of sampling frequency compared with a force platform permanently mounted in a laboratory. Finally, higher sampling frequency requires larger data files and, thus, more disk storage space and processing time. As a result, there is inconsistency in the research literature as to the sampling frequency used during performance measurement from a force platform. Therefore, determining the effect of sampling frequency–and, perhaps more importantly, what minimum sampling frequency can be used for this form of performance analysis–will be

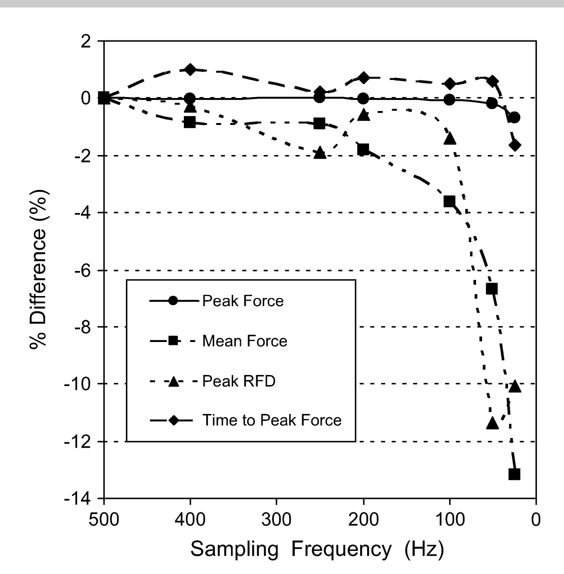

Figure 3. Percentage differences between force and related variables derived from the reference 500-Hz data and successively lower sample rates. RFD = rate of force development.

Table 2. Peak power.

	Mean (W)	*SD* (W)	% Difference	*SD* (%)	Pearson *r*
500 Hz	4299	685			
400 Hz	4308	686	0.20	0.06	1.00
250 Hz	4338	694	0.89	0.24	1.00
200 Hz	4356	697	1.31	0.26	1.00
100 Hz	4444	716	3.34	0.66	1.00
50 Hz	4582	754	6.51	1.63	1.00
25 Hz	4694	808	9.03	3.86	0.98

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Table 3. Mean power.

	Mean (W)	*SD* (W)	% Difference	*SD* (%)	Pearson *r*
500 Hz	1889	344			
400 Hz	1864	346	−1.35	2.72	0.99
250 Hz	1876	330	−0.56	3.69	0.98
200 Hz	1858	334	−1.50	3.96	0.98
100 Hz	1838	353	−2.80	4.25	0.98
50 Hz	1808	345	−4.18	6.65	0.92
25 Hz	1752	381	−7.28	9.40	0.87

Table 5. Mean force.

	Mean (N)	*SD* (N)	% Difference	*SD* (%)	Pearson *r*
500 Hz	1408	204			
400 Hz	1395	202	−0.85	1.22	1.00
250 Hz	1395	201	−0.88	1.91	0.99
200 Hz	1382	198	−1.80	1.67	0.99
100 Hz	1357	201	−3.63	2.13	0.99
50 Hz	1314	196	−6.67	3.39	0.97
25 Hz	1222	190	−13.17	5.06	0.92

important to inform scientists and practitioners when selecting a force platform and sampling frequency.

The purpose of this study was to examine the within-session reliability of several variables commonly used to characterize jump performance. Further, the influence of reducing sampling frequency on force, velocity, and power values and their reliability with 7 different sampling frequencies (500, 400, 250, 200, 100, 50, and 25 Hz) was examined. Measurements describing the shape of force-time curve (peak force, mean force, peak rate of force development [RFD], and time to peak force), velocity-time curve (peak and minimum velocity), and power-time curve (peak power, mean power, average rate of power development [RPD], and time to peak power) were analyzed to assess some commonly used strength diagnosis measures. In theory, the higher the sampling frequency, the more accurate the obtained values are. Because commonly cited previous studies (7–9,19) sampled GRF-time data at 500 Hz, this sampling frequency was considered as the reference. However, other papers (11) have reported the data sampled at a frequency of 200 Hz, and thus it is important to assess the validity of such data. Further, scientists and practitioners need information as to the effect of lower-frequency sampling so that they can make informed decisions balancing accuracy with reducing data file sizes and, perhaps, using cheaper and more portable force platforms.

Methods

Experimental Approach to the Problem

Twenty-four men were recruited into this study. The subjects performed CMJs on a force platform, and GRF-time data were sampled at a rate of 500 Hz and stored on a computer hard disk. The data were then resampled using interpolation techniques to produce GRF-time data sampled at 6 different frequencies of 400, 250, 200, 100, 50, and 25 Hz. Before testing, all subjects had 1 session of familiarization and practiced CMJs until they felt adequately familiarized. Two trials were recorded for each subject so that within-session reliability could be examined. The trials that exhibited the highest peak power value calculated from GRF-time data sampled at 500 Hz were used for statistical analysis.

Subjects

Twenty-four men were recruited from the university student population. Most of these subjects were regularly participating in some type of physical activity such as weight training, running, swimming, cycling, and/or ball games (e.g., soccer) 2–3 times per week on average. Subjects' age, height, and

Table 4. Peak force.

	Mean (N)	*SD* (N)	% Difference	*SD* (%)	Pearson *r*
500 Hz	1836	306			
400 Hz	1836	306	−0.01	0.02	1.00
250 Hz	1836	306	0.00	0.02	1.00
200 Hz	1835	305	−0.03	0.06	1.00
100 Hz	1835	305	−0.06	0.09	1.00
50 Hz	1832	306	−0.20	0.27	1.00
25 Hz	1824	304	−0.68	0.61	1.00

Table 6. Peak velocity.

	Mean ($m \cdot s^{-1}$)	*SD* ($m \cdot s^{-1}$)	% Difference	*SD* (%)	Pearson *r*
500 Hz	2.79	0.24			
400 Hz	2.79	0.24	−0.03	0.10	1.00
250 Hz	2.79	0.24	0.03	0.20	1.00
200 Hz	2.79	0.24	0.04	0.11	1.00
100 Hz	2.80	0.24	0.19	0.18	1.00
50 Hz	2.81	0.24	0.44	0.57	1.00
25 Hz	2.80	0.22	0.23	0.23	0.99

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TABLE 7. Minimum velocity.

	Mean ($m \cdot s^{-1}$)	*SD* ($m \cdot s^{-1}$)	% Difference	*SD* (%)	Pearson *r*
500 Hz	−1.20	0.18			
400 Hz	−1.20	0.18	0.00	0.00	1.00
250 Hz	−1.20	0.18	0.05	0.33	1.00
200 Hz	−1.20	0.18	0.15	0.31	1.00
100 Hz	−1.19	0.18	0.57	0.45	1.00
50 Hz	−1.17	0.17	2.18	1.21	1.00
25 Hz	−1.10	0.17	8.42	4.41	0.96

body mass were (mean ± *SD*) 25.0 ± 4.4 years, 176.5 ± 7.9 cm, and 79.3 ± 10.7 kg, respectively. Before the testing session, the subjects rode on a stationary bike for 5 minutes at 100-W intensity and 60 rpm for warm up. This study was approved by the university's human research ethics committee. All subjects read an information letter explaining the procedure of the study and signed an informed consent document.

Countermovement Jump

During the CMJ, the subjects first stood upright, then squatted to a self-selected depth of approximately 90° knee flexion, and jumped immediately as high as possible without pausing. During these jump movements, the subjects kept their hands on their hips. The jumps were performed on a force platform (Quattro Jump, Type 9290AD, Kistler, Switzerland), and the vertical component of GRF was sampled at a rate of 500 Hz for 10 seconds using dedicated software (Ballistic Measurement System, Fitness Technology, Australia); the data were saved on the computer hard drive. To control the effects of different filtering techniques on the values, GRF-time data were not filtered in this process (20). After the data on all subjects had been collected, the data files were opened and resampled to 400, 250, 200, 100, 50, and 25 Hz using a custom computer program written in VB.NET (Microsoft, Redmond, Wash) by interpolating between points to assemble a series of data sets corresponding to these frequencies. Briefly, this software performed the following procedure: 3 samples were inserted using linear interpolation between every 2 consecutive samples in the measured force-time data (i.e., 500 Hz), thus producing a new data set with an effective sample frequency of 2000 Hz. Then, every 5th, 8th, 10th, 20th, 40th, and 50th time point was drawn from this data set to create new sets of data effectively sampled at 400, 250, 200, 100, 50, and 25 Hz. Once 7 different GRF-time data sets were obtained, velocity of the system center of gravity (COG) was obtained from each GRF-time data set using the forward dynamics approach. This calculation is based on the relationship that change in momentum is equal to the impulse applied, which is the integral (trapezoid method) of the force-time data (6,12). Thus, velocity at each time point was calculated from the changes in momentum and the subject's body mass. Data sampling was started when the subject was completely still; it was assumed that the velocity of COG at the initial time point was 0 $m \cdot s^{-1}$.

As summarized in Figure 1, the beginning of the eccentric phase was determined where force started to decrease, the end of the eccentric phase (i.e., beginning of concentric phase) was determined where velocity changed from negative to positive, and the end of the concentric phase was determined where GRF became 0 N. Power at each time point was calculated as a product of GRF and velocity of COG. Peak power and peak velocity were determined as the highest values during the concentric phase of the jump. Minimum velocity was determined as the lowest value during the eccentric phase. Mean power was determined as the average power output between the following time points: 1) when the concentric phase began and 2) when the concentric phase ended. Peak force was defined as the highest force before the takeoff (i.e., not the impact force at landing). Mean force was the average between the following time points: 1) beginning of concentric phase and 2) end of concentric phase. Peak RFD was defined as the highest rate of change in GRF during a given 30-millisecond epoch before takeoff (17). Time to peak force was defined as the time difference between the following time points: 1) beginning of eccentric phase and 2) time point when peak force occurred. Time to peak power was defined as the time difference between the following: 1) beginning of concentric phase and 2) time when peak power was produced. Average RPD was obtained from peak power divided by time to peak power (4).

Statistical Analyses

Reliability of measurement was calculated between the 2 trials using intraclass correlation coefficients (ICCs), and ICC > 0.70 was considered as a minimum acceptable reliability (2). In addition, coefficients of variation (CVs) were also calculated. The influences of sampling frequency on the

TABLE 8. Peak rate of force development.

	Mean ($N \cdot s^{-1}$)	*SD* ($N \cdot s^{-1}$)	% Difference	*SD* (%)	Pearson *r*
500 Hz	8757	3879			
400 Hz	8733	3874	−0.27	0.30	1.00
250 Hz	8591	3803	−1.88	1.04	1.00
200 Hz	8707	3872	−0.57	0.61	1.00
100 Hz	8639	3854	−1.41	1.37	1.00
50 Hz	7761	3399	−11.37	4.86	0.99
25 Hz	7898	3703	−10.09	6.35	0.99

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Table 9. Time to peak force.

	Mean (ms)	*SD* (ms)	% Difference	*SD* (%)	Pearson *r*
500 Hz	0.686	0.181			
400 Hz	0.692	0.177	1.01	1.75	1.00
250 Hz	0.688	0.182	0.24	2.04	1.00
200 Hz	0.690	0.178	0.71	2.03	1.00
100 Hz	0.690	0.182	0.50	1.87	1.00
50 Hz	0.691	0.185	0.60	2.62	1.00
25 Hz	0.678	0.195	−1.65	5.41	0.98

Table 11. Time to peak power.

	Mean (ms)	*SD* (ms)	% Difference	*SD* (%)	Pearson *r*
500 Hz	0.230	0.040			
400 Hz	0.230	0.039	0.19	0.70	1.00
250 Hz	0.231	0.040	0.61	0.72	1.00
200 Hz	0.231	0.039	0.44	1.02	1.00
100 Hz	0.233	0.041	1.52	2.06	0.99
50 Hz	0.237	0.040	3.22	3.96	0.98
25 Hz	0.232	0.046	0.77	7.74	0.93

dependent variables were examined by the percentage difference between reference 500 Hz and each lower frequency data set. Percentage differences for each variable from each data set were obtained as means of each individual's percentage difference, so that *SD*s of percentage differences were also calculated. Because the purpose of the present study was to provide readers the magnitude of error attributable to the reduced sampling frequencies, percentage differences from referenced values have been reported instead of statistical significance. If pairwise comparison is made using probability statistical techniques (e.g., paired-samples *t*-test, or repeated-measures 1-way analysis of variance), even a practically trivial difference can be detected as significant. However, the focus of this study is not whether the difference is statistically significant but, rather, whether such differences are practically meaningful or not. Pearson product-moment correlations between values obtained from 500 Hz and other sampling frequencies were also calculated to determine whether the effect of reduced sampling frequency was linear and systematic. Strength of correlation was interpreted as follows: $r > 0.9$ is nearly perfect, 0.7–0.9 is very high, 0.5–0.7 is high, 0.3–0.5 is moderate, 0.1–0.3 is small, and 0.1 or less is trivial (10).

Table 10. Average rate of power development.

	Mean (W·s^{-1})	*SD* (W·s^{-1})	% Difference	*SD* (%)	Pearson *r*
500 Hz	19608	6897			
400 Hz	19612	6802	0.10	0.64	1.00
250 Hz	19663	6899	0.28	0.72	1.00
200 Hz	19759	6798	0.87	0.91	1.00
100 Hz	19988	7080	1.83	2.10	1.00
50 Hz	20210	6817	3.30	3.41	1.00
25 Hz	21372	7602	8.74	8.40	0.98

Results

Visual inspection of power, force, and velocity data plotted against time for any trial with reduced sampling frequency data seemed to completely overlay the reference 500-Hz data. Whereas most measurements exhibited high reliability across the entire range of sampling frequencies, peak RFD and time to peak power did not meet the minimum acceptable ICC at several sampling frequencies (Table 1). Percent difference from the reference value for each measurement is plotted in Figures 2–4. It can be observed from these figures that there is a breakpoint in accuracy at less than 200 Hz where percentage differences from the referenced values suddenly increase in most of the measurements. However, for all variables calculated from reduced sampling frequency data, there were nearly perfect or very high correlations between values across all measurements and sampling frequencies.

Discussion

The main purpose of the present study was to determine the measurement reliability of key performance measures commonly used to quantify strength qualities of CMJ from GRF data. As presented in Table 1, most values seemed to be reliable across a range of sampling frequencies except for peak RFD and time to peak power. Particularly, peak power, peak force, and peak velocity were highly reliable (ICC = 0.92–0.98, CV = 1.3–4.1) regardless of sampling frequency. Further, we examined the effects of different sampling frequencies on the validity of CMJ performance measures. It is apparent that 200 Hz is somewhat of a breaking point where error attributable to the reduced sampling frequencies suddenly increases in magnitude for several measurements (Figures 2–4). Obviously, it would be a problem if the true difference between 2 test occasions or 2 groups were hidden within the error attributed to reduced sampling frequency. That is, the fundamental question is how much of the true

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difference scientists and practitioners are trying to detect. For example, Newton et al. (16) have reported that changes in peak power output values during CMJ as a result of 8 weeks of weighted jump squat training were 8.0% in their longitudinal study using highly competitive men's volleyball players. Young et al. (23) have reported that starters have 16.1% higher peak power during CMJ than nonstarters in a professional Australian Rules football club. As observed in Figures 2–4, if sampling frequency was 200 Hz or higher, percentage differences to the referenced values were less than ±2% in all measurements, which is far smaller than the difference reported in previous studies (16,23).

Sampling theorem generally dictates that the frequency of data measurement should be at least twice that of the signal of interest, which is known as the Nyquist criterion (5). For example, it is recommended to sample data at 20 Hz or higher for human locomotion (5) for which the fastest movements are less than 10 Hz, so that even 25 Hz satisfies this criterion. In reality, it is recommended that the sample frequency be at least 5–10 times the frequency of the signal of interest, or 50–100 Hz for human movements (5).

Peak power values seem highly reliable. Importantly, in considering ICC and CV, peak power seems to be a more reliable value than mean power (Table 1). As presented in Tables 2 and 3, there is some degree of difference between the reference values and values calculated from reduced sampling frequencies up to 9.03% in peak power, and −7.28% in mean power, although whether such differences are meaningful or not is dependent on the purpose of measurement. It is important to note that peak power values tended to be overestimated when sampling frequency was reduced. It is speculated that this overestimation might have occurred because of changes in force between the time points where peak power appears and one prior was concave rather than linear, and thus the impulse between these 2 time points was overestimated when the trapezoid method was applied for integration. Conversely, mean power seemed underestimated compared with the reference value as sampling frequency was reduced. However, it is important to note that the *SD* of percentage difference in mean power (2.72–9.40%) was much larger than that of peak power (0.06–3.86%). When individual data are examined, peak power was overestimated in all subjects when sampling frequency was reduced, but mean power was overestimated in some subjects and underestimated in other subjects. Also, it is important to note that the 2 time points need to be determined manually to calculate mean power, mean force, time to peak force, average RPD, and time to peak power. If sampling frequency is reduced, the sensitivity of determining the time-related values is reduced; thus, CVs in some of these measurements were suddenly enlarged when sampling frequency was 50 or 25 Hz (Table 1).

When force is applied toward the force platform, it is apparent that the GRF can vary over time. Although force is applied over a period of time, GRF is recorded only at the time points determined by sampling frequency (e.g., every 0.002 seconds if the sampling frequency is 500 Hz). In other words, a continuously varying phenomenon is being measured at discrete time points, with the assumption that change between successive samples is linear. If changes in force are too rapid to record at the given sampling frequency, the changes in force occurring between 2 consecutive samples will not be accurately represented. Thus, the rapid change in force could be missed when GRF was sampled at lower frequencies (i.e., longer duration between 2 time points sampled), such as 50 or 25 Hz (Tables 4 and 5).

Power is obtained from GRF multiplied by instantaneous velocity at each time point. As well as the differences in GRF across the range of sampling frequencies, the differences in velocity values between different sampling frequencies were another reason why there were differences in power values. Using the forward dynamics approach, instantaneous velocity is determined from changes in momentum over the sample period (i.e., 1 / sampling frequency). Changes in momentum occur only as a result of force applied over this period, so it is impossible to determine the instantaneous velocity from any single time point. To determine the changes in momentum over a period of time, impulse is obtained by integration of the GRF-time curve. In the process of integration, there is a possible source of error if the force curve between consecutive time points is not a straight line. As a result, power output values may be overestimated or underestimated. In particular, the rapid changes in GRF cannot be accurately integrated if sampling frequency is too low (20). This could be the reason why the magnitude of error became larger as sampling frequencies became lower (Tables 6 and 7).

Peak RFD and time to peak force were measured to examine whether there was any influence of reducing sampling frequencies on the shape of the force-time curve. The reliability of peak RFD did not even meet the minimum acceptable ICC obtained from 500 Hz (Table 1). It is important to note that the rapid force development in CMJ is produced during the eccentric phase, and a good jumper can keep exerting high force rapidly (18). Therefore, peak RFD may appear during the eccentric phase for some and during the concentric phase for others, depending on each subject's jump technique (e.g., how rapidly and deeply he or she squats during the eccentric phase, how much force he or she generates during the concentric phase). In the present study, depth and tempo of squatting were not restricted. As a result, peak RFD values of some subjects could appear during the eccentric phase, and those of other subjects could appear during the concentric phase. Such inconsistency might be the reason why the reliability of peak RFD was low and the *SD* of this measurement was large. Normally, peak RFD is determined during a squat jump, which is concentric only to minimize these reliability issues.

In the present study, time to peak power and average RPD were measured to examine whether there was any influence of reducing sampling frequency on the shape of the power-

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time curve. As a next step, because the present study confirmed these measurements as reliable, future research should examine the importance of average RPD. Although many studies have reported the peak power and/or mean power, only 1 study (4) has reported the shape of the power-time curve described by average RPD to date. Because this is a novel performance diagnosis measure, we decided to include it in the current study. Cormie et al. (4) examined the influence of external load on average RPD during CMJs and weighted jump squats and reported significant effects. In future studies, the relationship to athletic performance (e.g., vertical jump height, sprint time, or playing division) and/or adaptation to a training intervention of average RPD would be of interest for scientists and practitioners. Based on our findings, RPD is reliable and relatively easy to determine from GRF data.

In summary, the present study examined the reliability of performance qualities measured from GRF data using the forward dynamics approach during CMJ as well as the influence of sampling frequency on these values. Whereas peak power, peak force, and peak velocity exhibit especially high reliability, all but 2 values (peak RFD and time to peak power) satisfied a minimum acceptable reliability (Table 1). Although there were differences up to 13.7% between values obtained from the reference (500 Hz) and 400 Hz or lower sampling frequency in some measurements, the present study also found nearly perfect or very high correlations in all measurements, indicating that the effect of reduced sampling frequency on these measures is highly linear and systematic (Tables 2–11). When sampling frequencies and percentage differences were plotted, it was noted that the differences markedly increased at 100 Hz in peak power, mean power, and mean force (Figures 2–4). On the other hand, if sampling frequency was 200 Hz or higher, ranges in percentage differences were less than $\pm 2\%$ in all measurements, which is far smaller than the changes that scientists and practitioners would have a meaningful interest in. As a result, the following practical application was concluded. In future investigations, it is necessary to examine whether the findings of the present study are applicable to other subject populations, such as athletes of different sports and training status (e.g., volleyball, basketball, jumping events in track and field, elite vs. subelite), as well as the influence of gender.

Practical Applications

This study has confirmed that peak power, peak force, and peak velocity are highly reliable measurements when recorded during CMJ and calculated using a force platform and GRF. Therefore, scientists and practitioners are encouraged to consider this methodology and these variables as valid and reliable measures to quantify athlete performance. In addition, average RPD also seems to be reliable, and thus future investigation should examine the usefulness of this novel measurement. On the other hand, reliability of peak RFD and time to peak power were not sufficient. Insufficient reliability of peak RFD could be attributable to the variance of technique of CMJ between subjects. Thus, if scientists and practitioners are particularly interested in this measurement, it seems necessary to restrict and standardize subjects' movement patterns (e.g., range of motion of countermovement) or to use a concentric only jump test. For example, Wilson et al. (21) used a Smith machine with mechanical stops to control the depth of countermovement. However, such restricted movement is less specific to typical tasks in sport, and so validity of such methodology may need to be carefully considered.

Theoretically, scientists and practitioners are recommended to use a force platform with the highest possible sampling frequency. However, in considering acceptable reliability, less than 2% difference from the reference values in all measurements, and nearly perfect correlation, scientists and practitioners may consider the use of sampling frequencies as low as 200 Hz if necessary. In general, force platforms with higher portability are accompanied with lower sampling frequency. In many instances, scientists and practitioners use force platforms at the actual training site rather than the laboratory, and thus portability of equipment is an important issue to be considered. Also, lower sampling frequency with reduced disk storage space is helpful to scientists and practitioners when they transfer sampled data using e-mail or USB external drives. Most importantly, scientists and practitioners need to keep sampling frequency consistent at all testing occasions, no matter which sampling frequency is selected, to allow valid comparison of performance variables across time.

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