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Research article

Number of successive cycles necessary to achieve stability of selected ground reaction force variables during continuous jumping

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Abstract

Because of inherent variability in all human cyclical movements, such as walking, running and jumping, data collected across a single cycle might be atypical and potentially unable to represent an individual's generalized performance. The study described here was designed to determine the number of successive cycles due to continuous, repetitive countermovement jumping which a test subject should perform in a single experimental session to achieve stability of the mean of the corresponding continuously measured ground reaction force (GRF) variables. Seven vertical GRF variables (period of jumping cycle, duration of contact phase, peak force amplitude and its timing, average rate of force development, average rate of force relaxation and impulse) were extracted on the cycle-by-cycle basis from vertical jumping force time histories generated by twelve participants who were jumping in response to regular electronic metronome beats in the range 2-2.8 Hz. Stability of the selected GRF variables across successive jumping cycles was examined for three jumping rates (2, 2.4 and 2.8 Hz) using two statistical methods: intra-class correlation (ICC) analysis and segmental averaging technique (SAT). Results of the ICC analysis indicated that an average of four successive cycles (mean 4.5 ± 2.7 for 2 Hz; 3.9 ± 2.6 for 2.4 Hz; 3.3 ± 2.7 for 2.8 Hz) were necessary to achieve maximum ICC values. Except for jumping period, maximum ICC values took values from 0.592 to 0.991 and all were significantly ($p \leq 0.05$) different from zero. Results of the SAT revealed that an average of ten successive cycles (mean 10.5 ± 3.5 for 2 Hz; 9.2 ± 3.8 for 2.4 Hz; 9.0 ± 3.9 for 2.8 Hz) were necessary to achieve stability of the selected parameters using criteria previously reported in the literature. Using 10 reference trials, the SAT required standard deviation criterion values of 0.49, 0.41 and 0.55 for 2 Hz, 2.4 Hz and 2.8 Hz jumping rates, respectively, in order to approximate the ICC results. The results of the study suggest that the ICC might be a less conservative but more objective method to evaluate stability of the data. Based on these considerations, it can be recommended that a force time history due to continuous, repetitive countermovement jumping should include minimum of four (the average from the ICC analysis) and possibly as many as nine successive jumping cycles (the upper limit of the ICC analysis) to establish stable mean values of the selected GRF data. This information is important for both experimental measurements and analytical studies of GRF signals due to continuous, repetitive countermovement jumping.

Key words: Reliability, stability, variability, jumping, ground reaction forces.

Introduction

A jumper starts a countermovement jump from an upright standing position, makes a downward movement by flexing the knees and hips, then immediately extends the knees and hips again to jump vertically up off the ground (Linthorne, 2000). When this action is performed continuously and repeatedly, the corresponding ground reaction force (GRF) time history is typically a series of distinctive pulses (Figure 1), which are the reaction to the force the body exerts on the supporting ground during the 'contact phase' of jumping. The pulses are separated by zero-force intervals which indicate 'aerial phases' of jumping when both feet leave the ground. Additionally, a jumping cycle is the period of time between any two nominally identical events in the jumping process. In the context of this paper, the instant at which the feet hit the ground (also known as 'initial contact') yielding a new pulse was selected as starting (and completing) event.

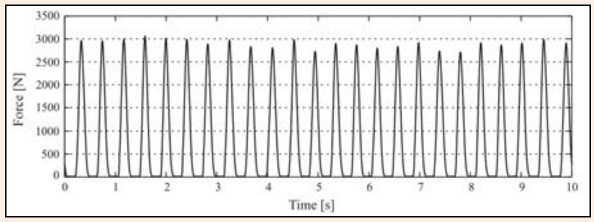

Figure 1. Example of a vertical jumping force record due to test subject 3 continuously jumping at 2.4 Hz jumping rate.

Apparent variability of the vertical jumping GRF pulses on the cycle-by-cycle basis results from inherent inability of humans to repeat identical movement twice (Hamill and McNiven, 1990). Hence, using a single cycle in analytical studies of jumping GRFs, such as performance of athletes in sports biomechanics (Zatsiorsky, 2000) and mathematical modelling of jumping force signals in structural dynamics (Racic et al., 2010; Sim et al., 2008), may be both invalid and unreliable because of the potential inability of the single cycle to represent the individual's long-term performance (Bates et al., 1983). By chance the single cycle could represent an average jumping pulse but also might be atypical. Assuming that subjects do not tire significantly, several cycles can provide a more stable and representative average GRF pulse (James et al., 2007). Here, stability of jumping pulses refers to repeatability of pulse variables, such as peak force and pulse duration, across successive and continuously measured cycles over time.

The stability of a GRF variable across cycles is usually assessed using so called 'test-retest methods' (Bates et al., 1983; Hamill and McNiven, 1990; James et al., 2007), such as segmental averaging technique (SAT; see Methods). In a study on five male runners, Bates et al

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(1983) used this method to prove that eight out of ten measured GRF footfalls were statistically necessary to obtain stable mean values of 30 selected force variables. For walking, the results of the SAT suggested that selected GRF variables obtained from 20 test subjects asked to step on a force plate 20 times were sufficiently repeatable after only 10 steps (Hamill and McNiven, 1990). In nominally similar study on jumping, Rodano and Squardone (2002) reported that 12 cycles were needed to establish stability of selected joint kinetic variables, such as hip, knee and ankle internal forces and moments, derived from vertical GRFs due to nonconsecutive jumping (i.e. jumping with pauses between jumps). However, no similar study is available in the literature on the number of successive and continuously measured countermovement jumping cycles necessary to achieve stability of the corresponding GRF variables alone.

Apart from the SAT, James et al. (2007) utilized a more traditional test-retest method, called the intra-class correlation (ICC; see Methods), to examine the stability of selected GRF variables (peak force, impulse and rate of force development) in nonconsecutive landing. To perform a landing cycle, test subjects were asked to step-off an elevated platform and come down (land) to a force plate. Interestingly, different methods provided dissimilar results. An average of four trials was required to reach the stability according to the ICC analysis, whereas 12 trials were required when using the SAT. Hence, the authors advised that subjects in landing experiments should perform a minimum of four and possibly as many as eight nonconsecutive landing cycles (the upper limit of the ICC analysis) to achieve the stability of corresponding GRF data.

To address the stability of continuously measured countermovement jumping GRFs in a similar manner, the present study was designed with two goals in mind:

1. To determine the number of successive cycles necessary to achieve stability of the corresponding jumping pulse parameters, such as peak force and duration of contact phase. This is an important methodological consideration in the design of jumping experiments, as well as in the analytical studies of jumping GRF signals.
2. To utilize both SAT and ICC to examine the stability of jumping GRF variables on the cycle-by-cycle basis, hence to compare the results from different methods.

Methods

Data collection

Six male and six female volunteers (age 28.6 ± 3.1 years, body mass 69.0 ± 13.9 kg) participated in the experiment. The test protocol, approved by the Research Ethics Committee of the University of Sheffield, required that the participants should complete a Physical Activity Readiness Questionnaire and a preliminary fitness test (measuring blood pressure and resting heart rate) to check whether they were suited to the kind of physical activity required during the experiments. The test subjects wore non-restrictive sportswear (shorts and t-shirt or a tracksuit) and athletic trainers. Prior to testing, all test subjects received a 10 minute warm-up supervised by a qualified instructor, comprising stretching and jumping at self-selected rates. Following the warm-up, each subject was asked to jump on an AMTI BP-400600 force plate (Advanced Mechanical Technology, Inc., 2007) rigidly fixed to the laboratory floor. Subjects were given a constant metronome beat at 15 different jumping rates in the range 1.4-2.8 Hz. The range included slow and fast jumping frequencies and is cited commonly in the literature as comfortable for individuals (Ginty et al., 2001). Jumping exercises were performed in a quasi-random order and lasted for 25 seconds with a two minute rest between each. In feedback from the participants, 25 seconds of continuous jumping was commonly considered optimal, which supported the assumption that the stability was not affected by fatigue. Moreover, no further specific physiological reasons were observed to affect stability. The subjects were not given any explicit instructions about their jumping technique, but they were encouraged to move as if they were enjoying a lively concert or an aerobic exercise. The force time histories were sampled at 1000 Hz.

Data reduction

In a feedback on the test, the majority of participants agreed they would prefer bouncing (moving up and down while the feet are in the permanent contact with the ground) at lower frequencies if they were not asked explicitly to jump. Contrary to the reports published elsewhere (Ginty et al., 2001), they found slow jumping below 2 Hz uncomfortable and tiresome, hence the metronome beats difficult to follow. Consequently, morphology (size and shape) of the corresponding GRF pulses differed significantly for slow jumping on the cycle-by-cycle basis (Figure 2). This made some of the GRF variables (typically peak force amplitudes and their positions) very hard to define in the consistent manner for successive pulses, so the stability analyses used in this paper are ineffective for such force data. Therefore, 2 Hz jumping rate was selected as the lowest jumping frequency at which all participants started generating the characteristic single peak GRF pattern on the jump-by-jump basis (Figure 1). This happens when subjects land on the ground with both feet simultaneously during the contact phase. According to the feedback, tempos at 2.4 Hz and 2.8 Hz were selected as examples of moderate and fast jumping, respectively.

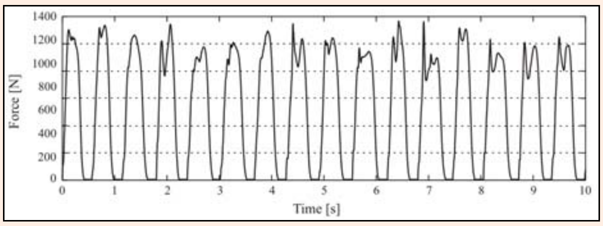

Figure 2. Force history generated by test subject 6 while jumping slowly at 1.6 Hz jumping rate.

Data pre-processing

Vertical GRF time histories were filtered using a fourth order low pass digital Butterworth filter with cut off

Table 1. **20-trial mean and (standard deviation) of selected GRF variables for all test subjects jumping at 2 Hz jumping rate.**

Subject #	Sex	Mass [kg]	T1 [s]	T2 [s]	T3 [s]	P [kN]	RFD [kN/s]	RFR [kN/s]	I [Ns]
1	male	87.5	.50 (.01)	.33 (.01)	.15 (.01)	2.748 (.070)	17.79 (1.23)	15.50 (.78)	430.96 (8.96)
2	male	97	.50 (.01)	.31 (.01)	.15 (.01)	3.15 (.08)	21.45 (1.60)	19.06 (1.12)	476.37 (13.81)
3	male	82	.50 (.01)	.27 (.01)	.11 (.004)	3.18 (.08)	27.74 (1.71)	19.78 (1.40)	401.91 (7.81)
4	female	63	.50 (.02)	.29 (.01)	.14 (.01)	1.94 (.06)	13.93 (1.79)	12.72 (.66)	295.55 (6.70)
5	female	57.5	.49 (.01)	.35 (.01)	.18 (.01)	1.53 (.04)	8.58 (.49)	8.81 (.61)	276.07 (5.71)
6	female	52.5	.50 (.02)	.32 (.02)	.14 (.02)	1.53 (.11)	11.11 (2.27)	8.38 (1.01)	254.44 (6.27)
7	female	60	.50 (.02)	.28 (.01)	.14 (.02)	1.84 (.09)	13.30 (1.97)	13.01 (1.63)	292.45 (8.90)
8	male	62	.50 (.03)	.32 (.02)	.14 (.02)	1.55 (.13)	11.70 (2.15)	8.51 (1.55)	252.74 (13.15)
9	female	68.5	.50 (.02)	.36 (.02)	.18 (.01)	2.02 (.09)	11.04 (1.20)	11.13 (1.09)	336.67 (13.97)
10	female	58.5	.50 (.01)	.31 (.01)	.16 (.01)	1.76 (.09)	11.01 (1.11)	11.68 (1.10)	283.09 (8.36)
11	male	60.5	.50 (.02)	.37 (.02)	.19 (.01)	1.71 (.86)	8.74 (0.70)	9.94 (.99)	295.51 (6.88)
12	male	79	.50 (.01)	.30 (.01)	.14 (.01)	2.72 (.08)	18.92 (1.10)	17.46 (.98)	388.90 (6.10)

frequency 100 Hz. 20 successive jumping cycles of a kind shown in Figure 3 were extracted from the middle of each force record. The force threshold criterion to identify the beginning of a jumping pulse (i.e. initial contact) and the ending point of the pulse was 15 N. Seven discrete variables were extracted for each jumping cycle (Figure 3): period of jumping cycle T_1 [s], contact phase interval T_2 [s], peak amplitude P [N], timing of the peak T_3 [s], average rate of force development RFD [$N \cdot s^{-1}$], average rate of force relaxation RFR [$N \cdot s^{-1}$], and impulse I [Ns]. RFD was calculated as the slope of the line of a jumping pulse from the initial contact (i.e. when the force is >15 N) to the peak (Figure 3). RFR was calculated as the slope of the line of a jumping pulse from the peak to the ending point (Figure 3). Impulse was calculated as the time integral of each GRF pulse from the initial contact to T_2. These variables were selected to represent different characteristics of the jumping GRF time history on the cycle-by-cycle basis, such as peak force amplitudes, timing, rates of force rise and decline and energy of the pulses. Moreover, they are analogous to variables analysed in previous reports on stability of GRF data during running (Bates et al., 1983), walking (Hamill and McNiven, 1990) and landing (James et al., 2007). Mean and standard deviation for 20 successive jumping cycles were calculated for each GRF variable and reported in Tables 1, 2 and 3.

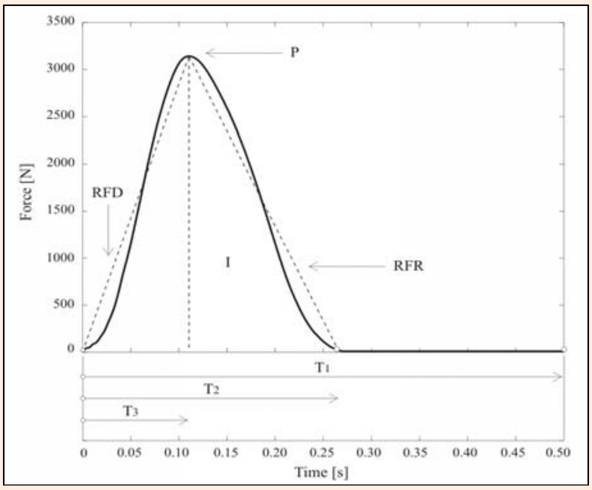

Figure 3. **An example of jumping force pulse and the seven discrete GRF variables due to jumping at 2 Hz jumping rate.**

Table 2. **20-trial mean and (standard deviation) of selected GRF variables for all test subjects jumping at 2.4 Hz jumping rate.**

Subject #	Sex	Mass [kg]	T1 [s]	T2 [s]	T3 [s]	P [kN]	RFD [kN/s]	RFR [kN/s]	I [Ns]
1	male	87.5	.42 (.01)	.30 (.01)	.13 (.01)	2.68 (.07)	20.15 (1.33)	15.67 (.64)	355.74 (6.18)
2	male	97	.42 (.01)	.29 (.01)	.14 (.004)	3.00 (.05)	22.12 (0.76)	18.95 (.50)	395.09 (6.35)
3	male	82	.42 (.01)	.26 (.01)	.11 (.01)	2.88 (.09)	25.60 (2.01)	19.06 (.90)	335.01 (9.99)
4	female	63	.42 (.01)	.26 (.01)	.11 (.004)	1.97 (.06)	17.05 (1.08)	13.14 (.81)	248.87 (6.35)
5	female	57.5	.42 (.01)	.31 (.01)	.15 (.01)	1.57 (.03)	10.25 (.54)	9.86 (.51)	233.21 (5.28)
6	female	52.5	.42 (.01)	.29 (.01)	.13 (.01)	1.61 (.11)	12.58 (1.73)	10.11 (1.36)	209.83 (8.40)
7	female	60	.42 (.01)	.26 (.01)	.12 (.01)	1.75 (.08)	14.58 (2.12)	12.80 (.81)	245.44 (9.86)
8	male	62	.42 (.02)	.29 (.02)	.13 (.01)	1.61 (.11)	12.58 (1.73)	10.11 (1.36)	209.83 (8.40)
9	female	68.5	.42 (.02)	.30 (.01)	.14 (.01)	1.97 (.06)	13.53 (1.06)	12.20 (1.02)	280.43 (9.24)
10	female	58.5	.42 (.01)	.26 (.01)	.12 (.01)	1.94 (.05)	15.54 (1.11)	14.57 (.66)	238.46 (9.83)
11	male	60.5	.43 (.02)	.29 (.01)	.13 (.01)	1.98 (.09)	15.02 (1.77)	12.19 (.85)	258.08 (7.28)
12	male	79	.42 (.01)	.28 (.01)	.13 (.01)	2.51 (.06)	19.59 (1.35)	16.34 (.77)	321.02 (7.61)

Table 3. 20-trial mean and (standard deviation) of selected GRF variables for all test subjects jumping at 2.8 Hz jumping rate.

Subject #	Sex	Mass [kg]	T1 [s]	T2 [s]	T3 [s]	P [kN]	RFD [kN/s]	RFR [kN/s]	I [Ns]
1	male	87.5	87.5	.36 (.01)	.25 (.01)	.11 (.004)	2.63 (.06)	23.66 (1.21)	18.10 (.88)
2	male	97	97	.36 (.01)	.25 (.005)	.11 (.005)	2.98 (.06)	25.93 (1.05)	21.92 (1.03)
3	male	82	82	.36 (.01)	.23 (.01)	.10 (.004)	2.75 (.08)	27.25 (1.58)	20.67 (1.38)
4	female	63	63	.35 (.01)	.23 (.01)	.10 (.004)	2.06 (.06)	20.51 (1.30)	16.26 (1.63)
5	female	57.5	57.5	.36 (.01)	.24 (.01)	.11 (.01)	1.68 (.06)	14.76 (1.10)	12.75 (1.03)
6	female	52.5	52.5	.36 (.02)	.25 (.02)	.11 (.01)	1.65 (.09)	14.46 (1.78)	12.11 (1.55)
7	female	60	60	.36 (.01)	.23 (.01)	.10 (.01)	1.80 (.06)	17.37 (1.35)	14.13 (.88)
8	male	62	62	.36 (.01)	.25 (.01)	.11 (.01)	1.64 (.05)	14.45 (1.55)	12.00 (.62)
9	female	68.5	68.5	.36 (.01)	.25 (.02)	.12 (.01)	2.01 (.06)	16.97 (1.37)	14.71 (1.74)
10	female	58.5	58.5	.35 (.01)	.22 (.01)	.11 (.004)	1.93 (.04)	18.08 (0.74)	16.55 (.78)
11	male	60.5	60.5	.36 (.01)	.23 (.01)	.10 (.004)	2.29 (.06)	22.62 (1.33)	17.79 (1.75)
12	male	79	79	.35 (.01)	.25 (.01)	.11 (.004)	2.38 (.04)	20.93 (.74)	16.86 (.92)

Statistical analysis

The stability of the selected GRF variables was quantified using two test-retest methods. First, the ICC was selected as a traditional statistical method for determining stability of data. Then, the SAT was utilized to make possible a comparison with previous research on the stability of the joint kinetic variables due to jumping (Rodano and Squardone 2002), as well as with similar reports on stability of the selected GRF variables due to running (Bates et al., 1983), walking (Hamill and McNiven, 2002) and landing (James et al., 2007).

Intra-class correlation analysis: In using the ICC to assess inter-cycle stability of a selected jumping GRF variable, one constructs a table in which columns are successive jumping cycles (e.g. Cycle 1, Cycle 2, etc.), whereas the row variable represents different test subjects (e.g. Subject 1, Subject 2, etc.). In the present study, the corresponding table has 20 columns and 12 rows. The cell entries in each row are values of the variable generated by a single individual on the cycle-by-cycle basis (here due to 20 cycles). The aim of the ICC analysis is to assess the inter-cycle (column) effect in relation to the inter-subject (row) effect, using two-way ANOVA statistics (Shrout and Fleiss, 1979). The ICC coefficient ρ can be defined as a ratio (Model 3,1 after Shrout and Fleiss, 1979):

$$\rho = \frac{MSB - EMS}{EMS + (k-1)EMS} \qquad (1)$$

where k is the number of test subjects (rows). MSB is the mean-square estimate of between-subjects variance (also called 'inter-subject variability') which reflects the expectation that different subjects will generate different values of the selected GRF variables across successive jumping cycles. EMS is the mean-square estimate of within-subjects variance (known as 'intra-subject variability'), or error attributed to inability of a single subject to repeat values of selected GRF parameters on the cycle-by-cycle basis.

The ρ coefficient takes values between -1/(k-1) and 1. It will approach 1 when there is no variance within subjects, i.e. the ICC will be high when any given row tends to have the same score across the columns (Haggard, 1958). Values below 0.50 represent poor stability, values between 0.50 and 0.75 suggest moderate stability, whereas values above 0.75 indicate good stability (Portney and Watkins, 2000).

For any given value of ρ, such as $\rho = \rho^*$ ($0 < \rho^* < 1$), there is a reasonable number of trials to form a stable average. This number m can be estimated beforehand as (Shrout and Fleiss, 1979):

$$m = \frac{\rho^*(1-\rho_L)}{\rho_L(1-\rho^*)} \qquad (2)$$

where ρ_L is the lower bound from a specified confidence interval around the ICC coefficient, such as 95% interval. The confidence interval gives a range likely to include ρ^*, whereas the confidence level (e.g. 95%) determines how likely the interval is to contain the given value of ICC.

For a selected GRF variable, the ICC coefficient ρ defined by equation (1) was calculated initially across the first two jumping cycles, i.e. the first two columns in the corresponding 12x20 table. The calculation was then iteratively repeated in increments of one jumping cycle for the combination of successive cycles ranging from 3 to 20. The maximum ρ value for all iterations and the corresponding number of jumping cycles (i.e. column location) were determined. To add more statistical rigor to the analysis, the probability p (also called p-value) that the maximum ρ value was significantly different from zero (statistical significance was set to 0.05) was checked by the hypothesis of no intra-class correlation (Haggard 1958). 95% confidence interval upper and lower limits of the ρ were also determined (Haggard 1958). Moreover, the number of cycles necessary to reach ρ values of 0.80, 0.85, and 0.90 were estimated using equation (2). Nominally identical ICC analysis was also performed for each selected GRF variable due to jumping at 2 Hz, 2.4 Hz and 2.8 Hz.

Segmental averaging analysis: The SAT estimates stability of a variable by analyzing stability of the cumulative mean across a number of the variable samples (Hamill and McNiven, 1990), where each sample

Table 4. Summary of ICC analysis for 2 Hz jumping rate.

ρ	Statistic	T1	T2	T3	P	LR	UL	I	Mean (SD)
ρ-max	n-trials	3	8	2	3	2	7	3	4.5 (2.7)
	ICC	.299	.830	.843	.915	.893	.837	.986	
	p-value	.013	0	0	0	0	0	0	
	95%CI upper	.429	.882	.888	.941	.923	.886	.991	
	95%CI lower	.173	.762	.782	.878	.853	.771	.980	
ρ = .80	n-trials	-	5	2	2	2	5	2	3.3 (1.6)
ρ = .85	n-trials	-	-	-	2	2	-	2	2.0 (.0)
ρ = .90	n-trials	-	-	-	3	-	-	3	3.0 (.0)

corresponds to one jumping cycle. The cumulative mean is calculated as the average of each sample with all previous samples, thus it is also known as 'moving average'. Therefore, the final cumulative mean in this study was equal to the overall 20 sample mean. The stability is achieved as soon as a pre-defined degree of precision is observed. Here, the criterion for stability of a GRF variable was met when a sample cumulative mean, and the cumulative mean of all following samples, fell within 20 cycle mean ±0.25 of the mean standard deviation (Hamill and McNiven, 1990), as illustrated in Figure 4. This represents a conservative cut-off rule and has been already applied in the similar studies on running (Bates et al., 1983), walking (Hamill and McNiven, 1990) and landing (James et al., 2007). From this criterion, the number of successive jumping cycles necessary to reach a stable mean for each variable, test subject and jumping rate was calculated. These are further averaged over all variables and test subjects yielding the minimum number of successive jumps a test subject should perform at a given jumping rate in order to reach a stable mean for all GRF variables.

To examine differences in stability that might result from using a different sample size, the SAT analysis was repeated for a data set comprising not 25 but 10 successive cycles and a 0.25 standard deviation criterion value. The results will be discussed in the next section.

Results

Results from ICC analysis are summarized in Tables 4, 5 and 6, respectively, and the number of cycles corresponding to the maximum ρ values (ρ-max in Tables 4, 5 and 6) are plotted in Figure 5.

Using the ICC analysis, in average five successive cycles (mean 4.5 ± 2.7) during jumping at 2 Hz (Table 4) and four cycles during jumping at 2.4 Hz (mean 3.9 ± 2.6, Table 5) and 2.8 Hz (mean 3.3 ± 2.4, Table 6) were needed to achieve the maximum ρ values. However, one variable at 2 Hz, two variables at 2.4 Hz and three variables at 2.8 Hz jumping rate showed a ρ value less than 0.80 indicating moderate and sometimes poor stability of these variables on the cycle-by-cycle basis. Interestingly, all these variables were time related: T_1, T_2 and T_3. This suggested that jumping period, duration of jumping pulses and timing of the peak force became less stable as jumping frequency was increased. In contrast, stability of P, RFD, RFR and I variables increased by higher jumping rates (Tables 4, 5 and 6). Moreover, the corresponding ρ values higher than 0.80 and zero p-values indicated statistically significant stability of these variables at all

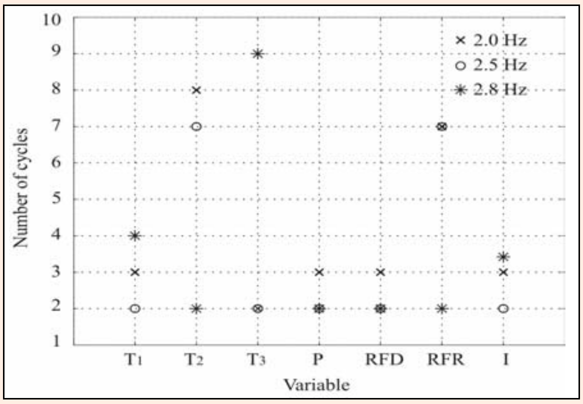

Figure 4. Summary of ICC analysis. Number of cycles corresponds to the maximum ρ values (ρ-max in Tables 4, 5 and 6).

Table 5. Summary of ICC analysis for 2.4 Hz jumping rate.

ρ	Statistic	T1	T2	T3	P	LR	UL	I	Mean (SD)
ρ-max	n-trials	2	7	2	2	2	7	2	3.9 (2.6)
	ICC	.143	.805	.758	.912	.850	.833	.991	
	p-value	.321	.000	.000	.000	.000	.000	.000	
	95%CI upper	.304	.863	.825	.938	.893	.884	.994	
	95%CI lower	-.026	.730	.672	.875	.791	.766	.988	
ρ = .80	n-trials	-	7	-	2	2	6	2	4.3 (2.6)
ρ = .85	n-trials	-	-	-	2	2	-	2	2.0 (.0)
ρ = .90	n-trials	-	-	-	2	-	-	2	2.0 (.0)

Table 6. Summary of ICC analysis for 2.8 Hz jumping rate.

ρ	Statistic	T1	T2	T3	P	LR	UL	I	Mean (SD)
ρ-max	**n-trials**	4	2	9	2	2	2	3	3.3 (2.4)
	ICC	.070	.606	.592	.969	.860	.884	.986	
	p-value	.217	.000	.000	.000	.000	.000	.000	
	95%CI upper	.174	.705	.691	.978	.898	.916	.990	
	95%CI lower	-.015	.487	.482	.957	.809	.840	.979	
ρ = .80	**n-trials**	-	-	-	2	2	2	2	2.0 (.0)
ρ = .85	**n-trials**	-	-	-	2	2	2	2	2.0 (.0)
ρ = .90	**n-trials**	-	-	-	2	-	-	2	2.0 (.0)

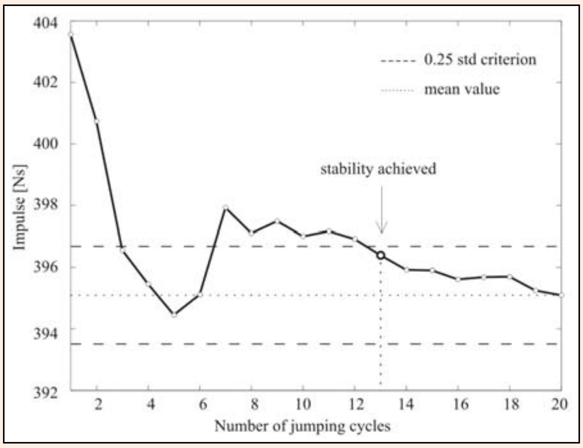

Figure 5. Graphical representation of the SAT for I variable due to test subject 2 jumping at 2.4 Hz jumping rate. Stability of the variable is achieved after 13 successive jumping cycles.

frequencies. Broadly speaking, the results of the ICC analysis suggest that the test-retest stability is relatively strong for majority of the selected GRF variables at slow and moderate jumping rates above 2 Hz and can be achieved within two to eight successive cycles. The stability during fast jumping rates is statistically significant for many of the selected GRF variables and can be achieved within two to nine successive cycles.

Results from SAT are summarized in Tables 7, 8 and 9 and illustrated in Figure 6. Using 20 reference cycles and a 0.25 standard deviation criterion value, the SAT suggested that as many as 11 successive cycles (mean 10.5 ± 3.5) performed at 2 Hz jumping rate, and as many as 10 successive cycles (mean 9.2 ± 3.8 and 9.0 ± 3.9) at 2.4 Hz and 2.8 Hz jumping rate, respectively, might be necessary to achieve stability of selected GRF variables. Similar to the study on landing (James et al., 2007), using ten reference cycles and a 0.25 standard deviation criterion value provided different results. It suggested that as many as seven successive cycles (mean 6.8 ± 1.9) might be necessary to achieve stability of the GRF data exhibited at 2 Hz and 2.4 Hz jumping rate, whereas at least eight successive cycles (mean 7.2 ± 1.5) were needed to reach stability of the pulse variables at 2.8 Hz jumping rate. This clearly illustrates limitations of the SAT. Many criteria, such as the number reference cycles and the standard deviation criterion value, are selected arbitrarily and influence the results. This will be discussed further in the next section.

Discussion

Stability of a GRF variable refers to the repeatability ofthat variable across repeated cycles over time and can be evaluated using test-retest reliability methods (James et al., 2007; Portney and Watkins, 2000). Stability is necessary for both the reliability of the data and its ability to

Table 7. Summary of the SAT analysis for 2 Hz jumping rate using 20 successive jumping cycles and 0.25 standard deviation criterion value.

Subject #	T1 [s]	T2 [s]	T3 [s]	P [kN]	RFD [kN/s]	RFR [kN/s]	I [Ns]	Mean (SD)
1	14	8	7	8	8	8	15	9.5 (3.1)
2	12	12	13	15	15	12	12	12.9 (1.4)
3	7	13	3	13	9	16	7	10.1 (4.3)
4	8	16	13	16	16	16	8	13.6 (3.6)
5	13	5	11	15	15	9	12	10.6 (4.0)
6	7	15	6	5	15	5	7	9.4 (4.7)
7	12	13	9	7	9	17	5	10.6 (3.9)
8	10	12	13	12	13	10	10	11.5 (1.3)
9	3	9	16	11	12	16	14	11.3 (4.3)
10	7	8	12	9	8	9	7	8.5 (1.6)
11	8	17	8	6	8	8	8	8.9 (3.4)
12	9	11	7	13	8	11	7	9.6 (2.2)
Mean (SD)	9.2 (3.2)	11.6 (3.6)	9.8 (3.8)	10.8 (3.8)	11.3 (3.3)	11.4 (4.0)	9.3 (3.2)	10.5 (3.5)

Table 8. **Summary of the SAT analysis for 2.4 Hz jumping rate using 20 successive jumping cycles and 0.25 standard deviation criterion value.**

Subject #	T1 [s]	T2 [s]	T3 [s]	P [kN]	RFD [kN/s]	RFR [kN/s]	I [Ns]	Mean (SD)
1	4	9	12	16	12	16	9	10.9 (4.0)
2	13	6	10	14	9	9	13	10.0 (3.1)
3	3	7	7	10	11	4	9	8.0 (3.4)
4	10	3	7	3	7	7	10	6.3 (3.0)
5	13	15	15	16	15	15	13	14.6 (1.1)
6	15	11	6	9	8	18	7	11.5 (4.9)
7	6	6	7	4	7	8	6	6.3 (1.2)
8	5	7	11	8	6	8	6	7.3 (1.8)
9	3	8	7	16	8	9	12	8.9 (3.8)
10	6	6	10	11	10	8	11	8.5 (2.3)
11	6	14	5	16	7	17	6	10.6 (5.1)
12	6	11	9	9	3	11	7	7.4 (3.2)
Mean (SD)	7.5 (4.2)	8.6 (3.6)	8.8 (2.9)	11.0 (4.7)	8.6 (3.1)	10.8 (4.5)	9.1 (2.7)	9.2 (3.8)

represent a more generalized long - term performance (validity). The number of cycles obtained from an individual in an experiment can influence stability (Bates et al., 1983; James et al., 2007) and thus is an important methodological consideration in both experimental data collection of jumping GRFs and their analytical studies. Therefore, one purpose of the present study was to determine the number of successive cycles needed to achieve stability of the selected GRF variables during continuous and repetitive countermovement jumping. Another purpose was to compare results from two different methods of determining stability.

Results from both ICC and SAT analysis indicated that several cycles were necessary to achieve stability of the selected GRF variables during continuous countermovement jumping. However, these methods provided dissimilar results. For example, the ICC analysis indicated the lowest stability of temporal parameters T_1, T_2 and T_3 (Tables 4, 5 and 6), whereas according to the SAT they achieved stability very often faster than the rest of the GRF variables (Tables 7, 8 and 9). If generalized to all jumping rates, the ICC analysis of the GRF data suggested that an average of four successive jumping cycles was necessary to achieve stability, whereas 11 successive cycles were needed using the SAT based on 20 reference cycles and 0.25 standard deviation criterion value. These values differ considerably and the decision to follow one recommendation over the others could affect duration and financial aspects of an experiment (James et al., 2007). The best method would utilize minimal number of arbitrary selected criteria for establishing stability and would be easy to implement. Bearing all this in mind, the ICC method has a definite advantage over the SAT. As in the case of landing (James et al., 2007), the SAT seems to provide a conservative estimate of the number of jumps to achieve stability, especially when using conventional 0.25 standard deviation criterion value reported elsewhere (Bates et al., 1983, Hamill and McNiven, 1990). However, it can be shown that for a sample comprising ten successive jumping cycles, the SAT provides results analogous to the ICC analysis for standard deviation criterion values of 0.49, 0.41 and 0.55 for 2 Hz, 2.4 Hz and 2.8 Hz jumping rates, respectively.

Table 9. **Summary of the SAT analysis for 2.8 Hz jumping rate using 20 successive jumping cycles and 0.25 standard deviation criterion value.**

Subject #	T1 [s]	T2 [s]	T3 [s]	P [kN]	RFD [kN/s]	RFR [kN/s]	I [Ns]	Mean (SD)
1	5	14	4	13	13	14	3	10.0 (5.0)
2	3	9	9	9	9	5	3	7.0 (2.8)
3	5	8	8	5	8	8	5	6.9 (1.6)
4	5	4	10	5	9	4	11	7.4 (3.2)
5	14	15	12	16	15	15	14	14.5 (1.2)
6	7	7	4	3	4	11	6	6.1 (2.5)
7	8	7	5	6	6	7	6	6.5 (0.9)
8	7	7	4	3	4	6	6	5.5 (1.6)
9	8	11	14	11	12	8	8	10.4 (2.2)
10	7	8	14	9	10	7	3	8.3 (3.1)
11	10	15	13	15	14	15	13	13.8 (1.8)
12	15	11	6	11	14	15	14	12.1 (3.0)
Mean (SD)	7.8 (3.6)	9.7 (3.6)	8.6 (4.0)	8.8 (4.5)	9.8 (3.9)	9.6 (4.2)	7.7 (4.3)	9.0 (3.9)

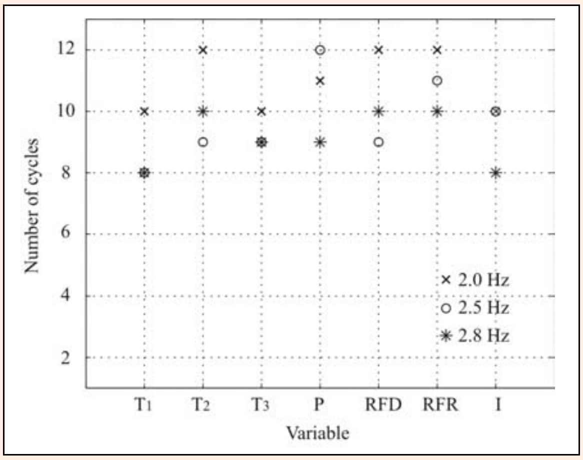

Figure 6. Summary of SAT analysis. Number of cycles is the minimum number of successive jumps necessary to achieve stability of the corresponding parameter.

In comparison with previous research that has reported the stability of selected GRF variables using the SAT (20 reference trials and 0.25 standard deviation criterion value), results from the present study suggest that less cycles might be needed to achieve stability of mean values of the selected GRF variables during continuous jumping than during nonconsecutive landing. During landing, the stability was reported following 12 nonconsecutive cycles (James et al., 2007). However, it was reported that eight nonconsecutive cycles were necessary to achieve stability of selected GRF variables during running (Bates et al., 1983). This is only one cycle less than in the present study on continuous jumping. On the other hand, the current results for jumping are similar to a previous report on walking (Hamill and McNiven, 1990) where the stability was achieved after 10 nonconsecutive steps. Although target variables and criterion values were different, the study which used the SAT (25 reference cycles and a 0.30 standard deviation criterion value) to conclude that 12 jumps were necessary to achieve stability in lower extremity joint kinetic variables derived from nonconsecutive jumping GRFs can be used for comparison with the results from the present study. A quite logical interpretation of the results is that jumping parameters can achieve stability of their mean faster during continuous jumping than during nonconsecutive jumping.

The main limitations of the study presented here are age, activity level and number of participants. All 12 test subjects are relatively young (age 28.6 ± 3.1 years) and recreationally active Caucasians. Future studies could examine if the current results are applicable to general human population characterized by wide diversity of age, race, activity level and geographical locations.

Conclusion

Several successive jumping cycles are necessary to achieve stability of GRF pulses during continuous countermovement jumping. Different statistical methods for evaluating stability of the data provided different results. If generalized to a range of jumping rates from 2 Hz to 2.8 Hz, an average of four successive jumping cycles was required for stability of selected GRF variables when using the ICC analysis and 11 cycles were required when using the SAT with the selected criteria. When comparing the two methods, the SAT would appear to provide a conservative estimate when using the criteria previously reported in the literature. On the other hand, the ICC analysis provided a traditional and more objective statistical method for determination of stability. Using the ICC analysis, many of the selected GRF variables achieved stability after only two successive cycles, whereas other variables required seven to nine cycles each. However, time related variables, such as jumping period, duration the contact phase and timing of the pulse peak amplitude never achieved an ICC of 0.80, regardless of the number of cycles performed. In contrast, other variables achieved ICC values greater than 0.95 as soon as after few successive cycles. Providing the subject does not tire considerably, based on the results presented in this study it can be recommended that a minimum of four successive cycles (the average from the ICC analysis) and possibly as many as nine successive cycles (the upper limit of the ICC analysis) should be obtained from each subject in a single experimental session during continuous countermovement jumping.

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Key points

- The number of successive jumping cycles due to continuous, repetitive countermovement jumping obtained from a test subject during in a single testing session influences the stability of the corresponding ground reaction force variables on a cycle-by-cycle basis.
- Researchers have used different criteria and methods for determining stability of ground reaction force data for a variety of activities, making comparisons among studies and activities difficult.
- In the present study, segmental averaging technique indicated that an average of ten successive jumping cycles were necessary to achieve stability of the selected force parameters using criteria previously reported in the literature, while less conservative test-retest intra-class correlation (ICC) analysis showed that an average of four successive jumping cycles were necessary for stability.
- Based on these considerations, it can be recommended that a force time history due to continuous, repetitive countermovement jumping should include minimum of four (the average from the ICC analysis) and possibly as many as nine successive jumping cycles (the upper limit of the ICC analysis) to achieve stability of jumping force data on a cycle-by-cycle basis.
- Knowledge about the stability of jumping force data is an important to maximize reliability of their experimental and analytical characterizations.

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