The Impact of Sampling Frequency on Ground Reaction Force Variables

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Abstract

New portable and low-cost technologies for assessing limb loading may be useful in non-laboratory environments, but have relatively low sampling frequencies. The lowest recommended sampling frequency for impact kinetics has not been investigated. The purpose of this study was to determine the effect of sampling frequency on metrics of impact kinetics during landing, walking, and running. This was a retrospective analysis of bilateral drop vertical jumps, unilateral drop landings, treadmill running, and flat, inclined, and declined treadmill walking. Landing data were collected at 1920 Hz while walking and running data were collected at 1440 Hz. Impact kinetics were computed at the highest possible sampling frequency, and then data were continuously down-sampled to determine the impact on the following computed metrics: peak impact force, average LR, and impulse. The minimum sampling frequency to compute each outcome with 90%, 95%, and 99.5% accuracy when compared to the original sampling frequency were determined. To achieve 90% of the true value of impact force, a sampling frequency of 180Hz was needed for running, 62 Hz for bilateral landing, and 48 Hz for remaining tasks. For average LR, a sampling frequency of 1440 Hz was need for running, 63 Hz for inclined walking, 192 Hz for bilateral landing, and 48 Hz for the remaining tasks. For impulse, 48 Hz was required for all tasks. The results of this study provide future researchers with a guide for selecting the sampling frequency required to accurately assess impact kinetics during walking, landing, or running.

Keywords: Data processing; biomechanics; walking; running; landing

Introduction

Assessing impact kinetics during everyday and athletic movements can provide information about an individual's risk for sustaining a musculoskeletal injury. For example, increased peak vertical impact force during landing is prospectively associated with an increased incidence of anterior cruciate ligament (ACL) injuries in young female athletes (Hewett et al., 2005; Leppänen et al., 2017). Increased loading rate (LR) is associated with tibial stress fractures in recreational runners (Milner et al., 2006; Zadpoor and Nikooyan, 2011). Additionally, decreased vertical ground reaction force GRF peaks and impulse during walking have been reported in total hip arthroplasty and knee osteoarthritis patients, respectively (Mccrory et al., 2001; Wiik et al., 2017). To measure GRF researchers often use embedded force plates, considered the gold standard for such studies. However, these devices are not widely used in non-research settings due to expense and lack of portability. Portable force plates and force-sensing insoles are more affordable and practical for use in non-research settings and have also become more popular among researchers, but these devices often utilize lower sampling rates than those of lab-grade embedded force plates. With a low sampling rate, there is a concern that critical information will be lost and that the accuracy of impact kinetic outcomes will degrade.

Previous studies have determined that propulsive kinetic outcomes could be accurately assessed when sampling as low as 200 Hz (Hori et al., 2009) during the jumping phase of a countermovement jump. However, we currently lack an understanding of the relationship between sampling rate and the accuracy of kinetic outcomes for other tasks such as walking, running and landing. Because portable force-measuring devices employ various maximum sampling frequencies, it would be helpful for researchers and clinicians to know the lowest sampling frequency that can be used to accurately assess a desired outcome for a particular movement task. Such information would provide quantitative criteria for rejection of devices that do not meet the minimum frequency threshold. Therefore, the purpose of this study was to determine the effect of sampling frequency on impact kinetic outcomes during landing, walking, and running tasks.

Methods

Participants

This study was a secondary analysis of data collected during three previous studies. The first consisted of thirty participants who completed a landing protocol (Peebles et al., 2018); the second consisted of twenty participants who completed a treadmill running protocol (Peebles et al., 2021); and the third consisted of twenty participants who completed a waking protocol (Renner et al., 2019), Table 1.

For all studies, the participants met the following inclusion criteria: 1) between 18 and 30 years old, 2) recreationally active, defined as participating in physical activity at least three times per week for at least thirty minutes, 3) injury free, defined as not having had an injury in the previous three months and not having any current pain that impacted mobility, and 4) never had a major lower extremity injury or surgery. These studies were approved by the Virginia Tech Institutional Review Board, and participants signed forms that gave consent for both the primary studies and secondary data analysis.

Procedure

The landing protocol consisted of seven bilateral drop vertical jumps and seven unilateral drop landings on each limb. For the bilateral landing task, participants stood on a box (31 cm), jumped forward toward a target placed half their body height away from the box, completed a bilateral landing, and then immediately jumped vertically as high as possible (Bell et al., 2014; Peebles et al., 2021). For the unilateral drop landing task, participants stood on one foot on top of the box, dropped straight off, and landed on the ground with the same foot (Ithurburn et al., 2017; Peebles et al., 2021). Impact kinetics were measured throughout each landing at a sampling rate of 1920 Hz using two embedded force plates (AMTI, Watertown, Massachusetts).

The treadmill running protocol consisted of running on a fore-aft split-belt instrumented treadmill (AMTI, Watertown, MA) for one minute using a sampling rate of 1440 Hz (Peebles et al., 2021). Participants walked for 1 minute at a comfortable walking speed on the same instrumented treadmill at 0% incline, 10% incline, and a 10% decline. Participants ran and walked at their preferred speeds (Dingwell and Marin, 2006). Data from six participants in the running study did not have clearly defined impact peaks and were excluded from LR calculations. The average self-selected running speed was 2.72±0.47 m/s. The self-selected walking speed during the level walking was 1.23±0.26 m/s, for declined it was 1.22±0.33 m/s, and for inclined the average speed was 1.15±0.25 m/s.

Analysis

All data analysis was performed using unfiltered data in Matlab (MathWorks Inc., Nantucket, Massachusetts). During the bilateral landing task, the vertical GRF was analyzed for the first landing for each trial (Peebles et al., 2018). The first 200 ms of each unilateral landing trial were used for data analysis. In the running trials, each step during a ten-second window was analyzed, and ten steps were analyzed for each walking condition. Peak force, LR, and impulse were calculated for each task. For bilateral landing, peak impact force was calculated as the peak force that occurred in the first 30% of the ground contact phase (time between initial contact and toe-off) (Peebles et al., 2018). For unilateral landing, running, and walking, the peak impact force was determined as the first peak in force that occurred following initial contact (Milner et al., 2006). For all tasks initial contact was identified when the force exceeded 25 N (Peebles et al., 2018). For walking and running, toe-off was identified as the timepoint when the force dropped below 25N for 5 frames of data.

Average LR was computed as the peak impact force divided by the time between initial contact and peak impact force (Peebles et al., 2018) for both landing, and all walking conditions. For the running task, both the peak LR and average LR were computed using the linear portion of the force-time profile, which was identified between 20% and 80% of the time between initial contact and peak impact force (Milner et al., 2006). Finally, impulse was computed as the area under the force-time profile during the ground contact phase for bilateral landing, running, and walking (Peebles et al., 2018; Renner et al., 2019), and the first 200 ms following initial ground contact for unilateral landing (Peebles et al., 2018).

All study outcomes were computed using the raw, unfiltered force-plate data, which were considered as the 'true values' in the analysis. Then, the force plate data were consecutively downsampled until a sampling frequency of 48 Hz. This reduction was conducted by keeping every 2nd, 3rd, 4th, etc. data points, creating new sampling frequency datasets (Hori et al., 2009). Outcomes were computed at each stage of the downsampling process (Figure 1). A detailed list of sampling frequencies is available as supplemental material.

The error was computed at each sampling frequency as the percent difference relative to the true value for each trial, and then averaged across trials for each participant. The sampling frequency required to achieve 99.5%, 95% and 90% of the true value was then identified. The outcomes from the downsampled data were plotted against the modeled sampling frequency (Figure 2). Additionally, an intraclass correlation coefficient (ICC) was calculated using the norm-referenced reliability calculation (ICC(C,1) in Matlab) for each task and variable of interest. For example, if the original sampling frequency was 1440 Hz the first ICC was calculated between 1440 Hz and 720 Hz, then the ICC was calculated between 1440 Hz and 480 Hz and so on until an ICC was calculated between 1440 Hz and 48 Hz. An ICC above 0.90 was considered excellent, 0.75-0.89 good, 0.50-0.74 moderate and below 0.50 poor (Koo & Li, 2016).

Results

The true values for each kinetic outcome are presented in Table 2. The minimum recommended frequency to reach 90%, 95%, and 99.5% of the true value for each outcome is reported in Table 3. Across all conditions, LR was the most sensitive outcome to decreases in sampling frequency, and impulse was least affected. In general, running and bilateral landing were the movement conditions most sensitive to decreases in sampling frequency and walking and unilateral landing were least sensitive.

The peak GRF and impulse ICC analysis indicated excellent correlations with peak GRF with ICC values ≥0.93 and impulse ICC values ≥0.99 for all tasks and sampling frequencies. LR ICC values had greater variance between tasks. In flat walking, the ICC dropped below 0.90 at 48Hz (0.88), whereas inclined walking, declined walking, and unilateral landing LR remained in the excellent category for all sampling rates (>0.99). The ICC values for the average LR in running dropped to 0.89 at 103 Hz, 0.75 at 76 Hz, and 0.6 at 48 Hz. The ICC for peak LR during running decreased quicker, with an ICC of 0.88 at 180 Hz, 0.74 at 80 Hz, and 0.55 at 48 Hz. Finally, bilateral landing ICC values dropped to 0.89 at 77 Hz, 0.72 at 56.5 Hz, and 0.63 at 48 Hz. The ICC values for each sampling frequency tested can be found in the supplemental materials.

Discussion

The present study determined the impact of sampling frequency on peak impact force, LR, and impulse during a bilateral drop vertical jump, unilateral drop landing, as well as treadmill running and walking. The study results indicate that impulse was the least affected by sampling frequency and can be determined within 95% of the true value using a sampling frequency as low as 100 Hz. LR was the most sensitive to sampling frequency, which was likely the result of compounding the variance in the magnitude and timing of peak impact force, as well as the variance in the timing of initial contact. These findings are consistent with previous work, which found force-sensing shoe insoles (100 Hz) can accurately measure impulse during landing and running, but are less accurate when measuring LR (Peebles et al., 2018). Peak force and LR were sensitive to sampling frequency during running, which was likely due to the impact peak occurring very quickly during running and disappearing at lower frequencies.

One limitation of the present study was the choice to not filter the data. Force-plate data are often filtered (Bell et al., 2014; Hewett et al., 2005; Leppänen et al., 2017; Renner et al., 2018), which would likely affect the magnitude and timing of each study outcome. Additionally, it should be noted that this study analyzed the impact of down-sampling on force-plate data, which represent the force between the sole of the shoe and the ground. Many of the newer and more mobile technologies are in-shoe insoles, which record the force between the foot and the shoe. Owing to the material response of the sole of the shoe, the exact timing and magnitude of forces recorded from these two locations must be different in principle. However, the values are likely to be similar enough that our conclusions about down-sampling should be similarly applicable.

Previous research on the impact of sampling frequency has been conducted on tracking center of pressure (Koltermann et al., 2018) and GRF metrics during a counter movement jump (Hori et al., 2009). Both studies advise a sampling frequency of at least 100 Hz, with Hori et al. suggesting 200 Hz (Hori et al., 2009; Koltermann et al., 2018). This study indicates that a sampling rate of 100 Hz will be able to calculate the peak force and impulse within 0.5% of the true value and LR within 5% for walking. The more dynamic tasks have a wider range of minimum sampling rates. For running, a sampling rate of 1440 Hz should be used when assessing peak impact force and LR. A sampling rate of 500 Hz was sufficient for peak impact force and impulse during landing; however, a greater sampling rate was needed to reliably quantify LR. These results indicate that technology with lower sampling rates could be suitable for lower impact tasks such as walking, but investigators should consider the potential difference in metrics for more dynamic tasks.

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Figure 1: Representative data for each movement and outcome included in the present study. The original data (recorded at 1440-1920 Hz) are indicated with a thick blue line, and a representative downsampled dataset (recorded at 96 Hz) is shown with orange circles.

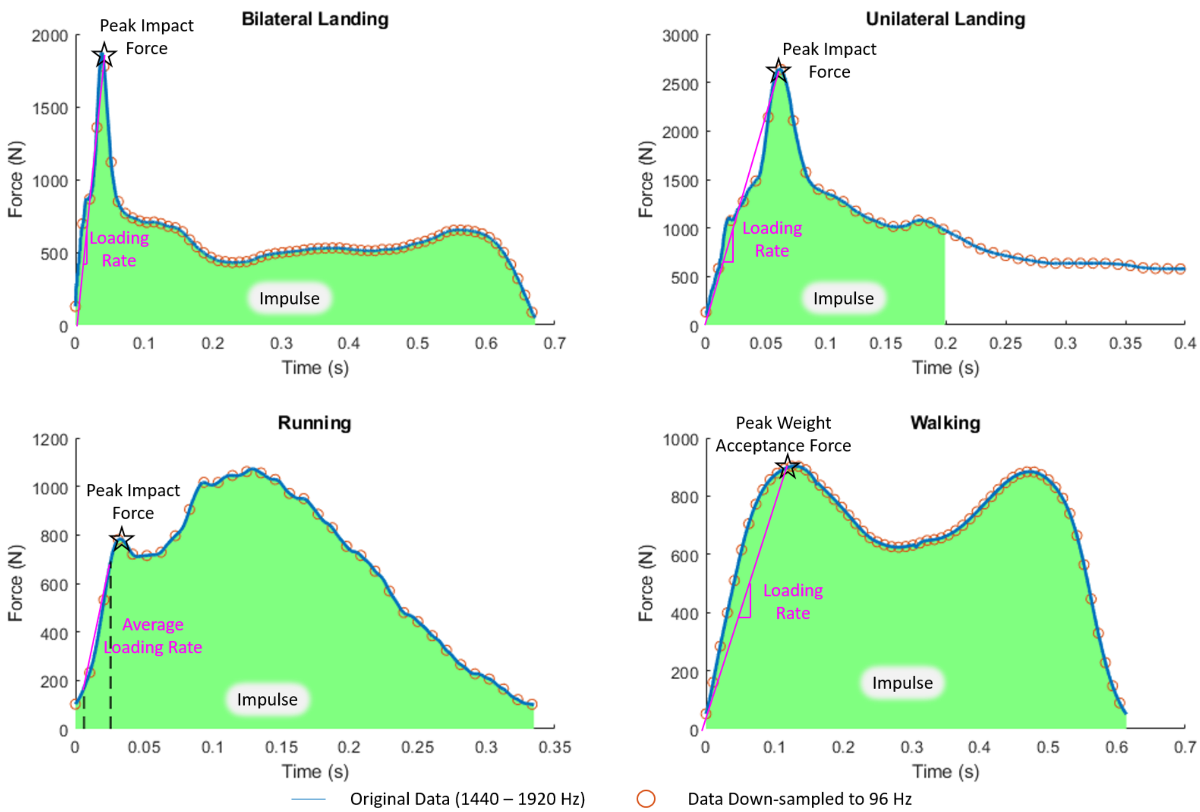

Figure 2: Relationship between sampling frequency and the true value for each outcome across A) bilateral landing, B) unilateral landing, C) treadmill running, D) flat treadmill walking, E) declined treadmill walking, and F) inclined treadmill walking. All error bars represent one standard deviation across study participants; in some cases, the bar cannot be seen because the standard deviation is smaller than the marker.

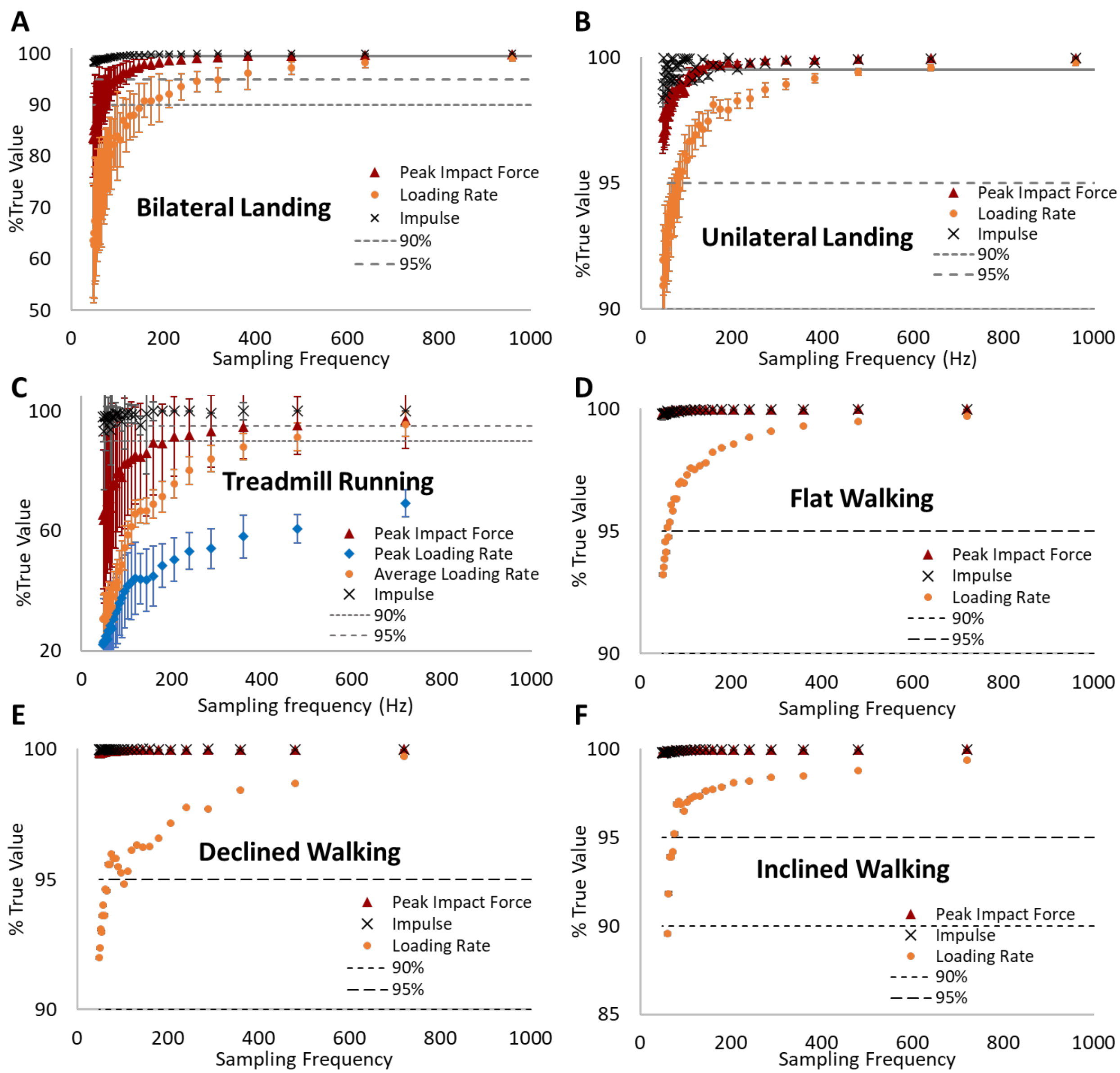

Table 1: Participant demographics for three studies that provided the original data to down-sample.

	Landing Study		Running Study		Walking Study	
	Male n =15	Female n =15	Male n =10	Female n =10	Male n =11	Female n =9
Age (years)	23.60 ± 2.20	22.93 ± 3.08	21.50 ± 2.27	22.20 ± 2.53	21.64 ± 2.62	22.89 ± 3.14
Height (m)	1.79 ± 0.07	1.72 ± 0.05	1.81 ± 0.06	1.69 ± 0.06	1.79 ± 0.08	1.68 ± 0.05
Weight (kg)	77.19 ± 15.11	63.46 ± 8.92	77.34 ± 11.62	63.56 ± 9.76	73.39 ± 8.95	67.80 ± 13.88

Table 2: True values for the kinetic outcome variables for each task. Values are normalized to body weight (BW) at 1920 Hz for the landing tasks and 1440 Hz for walking and running tasks. The running task lists both the average LR and the peak LR and the other tasks report the average LR.

	Impact Force (BW)	**LR (BW/s)**	**Impulse (BWs)**
Bilateral Landing	2.25 ± 0.56	64.29 ± 30.53	0.52 ± 0.06
Unilateral Landing	3.99 ± 0.61	78.46 ± 16.74	0.42 ± 0.04
Treadmill Running	1.560 ± 0.26	Peak: 169.30 ± 40.29 Ave: 64.39 ± 20.20	0.39 ± 0.07
Flat Walking	1.10 ± 0.09	6.37 ± 1.97	0.57 ± 0.05
Declined Walking	1.27 ± 0.16	9.54 ± 3.00	0.52 ± 0.04
Inclined Walking	1.02 ± 0.06	5.19 ± 1.80	0.58 ± 0.05

Table 3: Recommended minimum sampling frequency (in Hz) to achieve 90%, 95%, and 99.5% accuracy, relative to the True Value (TV), which was obtained at 1920 Hz for landing and 1440 Hz for treadmill running.

	90% TV	**95% TV**	**99.5% TV**
Bilateral Landing			
Peak Impact Force	62	96	384
Average LR	192	384	1920
Impulse	48	48	106
Unilateral Landing			
Peak Impact Force	48	48	137
Average LR	48	87	640
Impulse	48	48	148
Treadmill Running			
Peak Impact Force	180	480	1440
Peak LR	1440	1440	1440
Average LR	480	720	1440
Impulse	48	110	240
Flat Walking			
Peak Impact Force	48	48	48
Average LR	60	76	720
Impulse	48	48	48
Declined Walking			
Peak Impact Force	48	48	48
Average LR	48	111	720
Impulse	48	48	48
Inclined Walking			
Peak Impact Force	48	48	48
Average LR	63	76	720
Impulse	48	48	48

Supplemental Table 1: Detailed list of sampling frequencies for each iteration for the bilateral and unilateral landing tasks (Landing Tasks) and for walking and running data (Gait).

Iteration	Landing Tasks	Gait
1 (Original)	1920	1440
2	960.0	720.0
3	640.0	480.0
4	480.0	360.0
5	384.0	288.0
6	320.0	240.0
7	274.3	205.7
8	240.0	180.0
9	213.3	160.0
10	192.0	144.0
11	174.5	130.9
12	160.0	120.0
13	147.7	110.8
14	137.1	102.9
15	128.0	96.0
16	120.0	90.0
17	112.9	84.7
18	106.7	80.0
19	101.1	75.8
20	96.0	72.0
21	91.4	68.6
22	87.3	65.5
23	83.5	62.6
24	80.0	60.0
25	76.8	57.6
26	73.8	55.4
27	71.1	53.3
28	68.6	51.4
29	66.2	49.7
30	64.0	48.0
31	61.9	
32	60.0	
33	58.2	
34	56.5	
35	54.9	
36	53.3	
37	51.9	
38	50.5	
39	49.2	
40	48.0	

Supplemental Table 2: Exact ICC values for each sampling frequency for all walking tasks and running. Abbreviations: Peak GRF (GRF), Impulse (I), LR (LR), Average LR (LR-Avg), Peak LR (LR-Pk).

	Flat Walking			**Inclined Walking**			**Declined Walking**			**Running**			
	GRF	I	LR	GRF	I	LR	GRF	I	LR	GRF	I	LR-Avg	LR-Pk
720	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	0.98
480	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	0.99	0.96
360	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	0.98	0.96
288	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.99	0.96	0.96
240	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00	0.96	0.94
205.7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00	0.95	0.94
180	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.90	1.00	0.93	0.92
160	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.91	1.00	0.92	0.87
144	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	0.99	0.87	0.88
130.9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.99	0.87	0.89
120	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	0.99	0.89	0.89
110.8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.84	0.99	0.78	0.87
102.9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.99	0.76	0.86
96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.81	0.99	0.73	0.83
90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.74	0.82	0.63	0.73
84.7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.77	0.99	0.59	0.72
80	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	0.99	0.77	1.00	0.57	0.70
75.8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.74	1.00	0.42	0.58
72	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.73	0.99	0.44	0.58
68.6	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00	0.99	0.72	0.99	0.31	0.44
65.5	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.65	0.82	0.36	0.46
62.6	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.69	0.81	0.29	0.46
60	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	1.00	0.71	0.99	0.32	0.46
57.6	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.73	0.96	0.19	0.27
55.4	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.69	0.99	0.33	0.43
53.3	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.67	0.99	0.17	0.28
51.4	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.67	0.81	0.25	0.37
49.7	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	0.99	0.67	0.81	0.33	0.48
48	1.00	1.00	0.88	1.00	1.00	0.99	1.00	1.00	0.99	0.72	0.99	0.17	0.27

Key:	Excellent (≥0.90)	Good (0.75-0.89)	Moderate (0.50-.74)	Poor (<0.50)

Supplemental Table 3: Exact ICC values for each sampling frequency for bilateral and unilateral landing tasks. Abbreviations: Peak GRF (GRF), Impulse (I), LR (LR).

	Bilateral Landing			**Unilateral Landing**		
	GRF	I	LR	GRF	I	LR
960	1.00	1.00	1.00	1.00	1.00	0.97
640	1.00	1.00	1.00	1.00	1.00	0.97
480	1.00	1.00	1.00	1.00	1.00	0.98
384	1.00	1.00	0.99	1.00	1.00	0.99
320	1.00	1.00	0.99	1.00	1.00	0.99
274.3	1.00	1.00	1.00	1.00	1.00	0.99
240	1.00	1.00	0.99	1.00	1.00	0.98
213.3	1.00	1.00	0.99	1.00	1.00	0.99
192	1.00	1.00	0.97	1.00	1.00	0.99
174.5	1.00	1.00	0.97	1.00	1.00	0.99
160	1.00	1.00	0.99	1.00	1.00	0.98
147.7	1.00	1.00	0.98	1.00	1.00	0.99
137.1	1.00	1.00	0.98	1.00	1.00	0.98
128	1.00	1.00	0.98	1.00	1.00	0.98
120	1.00	1.00	0.96	1.00	1.00	0.99
112.9	1.00	1.00	0.98	1.00	1.00	0.98
106.7	1.00	1.00	0.93	1.00	1.00	0.98
101.1	1.00	1.00	0.95	1.00	1.00	0.99
96	1.00	1.00	0.94	1.00	1.00	0.97
91.4	0.99	1.00	0.93	1.00	1.00	0.99
87.3	0.99	1.00	0.90	1.00	1.00	0.98
83.5	0.99	1.00	0.90	1.00	1.00	0.98
80	0.99	1.00	0.92	1.00	1.00	0.97
76.8	0.99	1.00	0.89	1.00	1.00	0.99
73.8	0.98	1.00	0.85	1.00	1.00	0.96
71.1	0.98	1.00	0.86	1.00	1.00	0.96
68.6	0.98	1.00	0.84	1.00	1.00	0.98
66.2	0.98	1.00	0.78	1.00	1.00	0.99
64	0.97	1.00	0.81	1.00	1.00	0.96
61.9	0.97	1.00	0.75	1.00	1.00	0.98
60	0.98	1.00	0.78	1.00	1.00	0.96
58.2	0.97	1.00	0.76	1.00	1.00	0.95
56.5	0.95	1.00	0.72	1.00	1.00	0.97
54.9	0.96	1.00	0.72	0.99	1.00	0.98
53.3	0.93	1.00	0.65	1.00	1.00	0.97
51.9	0.95	1.00	0.68	0.99	1.00	0.96
50.5	0.95	1.00	0.63	0.99	1.00	0.94
49.2	0.94	1.00	0.58	0.99	1.00	0.96
48	0.93	1.00	0.63	0.99	1.00	0.96

Color Key:	Excellent (≥0.90)	Good (0.75-0.89)
	Moderate (0.50-0.74)	Poor (<0.50)