Journal of Strength and Conditioning Research™

Validity and Reliability of Force-Time Characteristics Using a Portable Load Cell for the Isometric Midthigh Pull

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Abstract

Pichardo, AW, Neville, J, Tinwala, F, Cronin, JB, and Brown, SR. Validity and reliability of force-time characteristics using a portable load cell for the isometric midthigh pull. *J Strength Cond Res* 38(1): 185–191, 2024—Many practitioners use the isometric midthigh pull (IMTP) to assess maximal strength in a safe, time-effective manner. However, expensive, stationary force plates are not always practical in a large team setting. Therefore, the purpose of this study was to establish the validity and between-session reliability of peak force, rate of force development (RFD), and impulse during an IMTP using 2 experimental protocols: a traditional fixed bar with a force plate (BarFP) and a flexible chain measured with a force plate (ChainFP) and a load cell (ChainLC). After a familiarization session, 13 resistance-trained men performed 3 trials of the BarFP condition and 3 trials of the chain-based conditions. The identical procedures were replicated twice more, with a week between each testing session. The main findings were (a) no RFD or impulse measures were found to achieve acceptable reliability across all methodological approaches and testing occasions; (b) peak force was reliable across all methods, with coefficient of variation ranging from 4.6 to 8.3%, intraclass correlation coefficient ranging from 0.94 to 0.98, and the least variability associated with the ChainLC condition; and (c) the ChainFP method was found to significantly underrepresent peak force by 4.8% ($p < 0.05$), with no significant differences between the ChainLC and BarFP methods. Therefore, the ChainLC would seem a valid, reliable, portable, and cost-effective alternative to force plates when assessing maximal isometric strength in the IMTP.

Key Words: peak force, rate of force development, impulse, strength, force-time curve

Introduction

The importance of muscular strength for sport performance is well established (24) and is a metric of great interest to strength and conditioning practitioners. Although there is a variety of maximal strength assessments, the isometric midthigh pull (IMTP) is a popular choice in the strength and conditioning community (3,6,7,16,23,25). The IMTP is often used as a safe and time-efficient alternative to assessing maximal dynamic strength using a compound movement, such as the clean pull or back squat. This test is usually performed with an athlete atop a force plate, pulling on a fixed bar with the corresponding ground reaction forces recorded. Peak force (PF), rate of force development (RFD) over different periods (usually ranging from 30 to 250 ms), and impulse are the most common variables measured to describe force production characteristics (16,21,23,25).

Despite the popularity of the IMTP as a strength assessment, a variety of methodological issues regarding posture (3,9,10), sampling frequency (7), data smoothing (5), and RFD calculation (12) may influence force-time variables and should be reported to allow for comparisons between studies (2). Several researchers have compared the effects of different knee and hip angles on kinetic variables of the IMTP (1,3,9,10). Specifically, Beckham et al. (1) and Guppy et al. (10) found significantly greater PF values in an upright position representing the second pull of the clean compared with a bent position with the bar midthigh. However, Comfort et al. (3) found that kinetic variables collected from an IMTP using a self-selected posture did not differ significantly from a range of standardized knee and hip angles and recommend using a self-selected posture to reduce familiarization time and the possibility of a learning effect. Regarding sampling frequency, Dos'Santos et al. (7) found no differences in kinetic variables sampled at frequencies of 500, 1,000, 1,500, and 2,000 Hz, whereas James et al. (16) found differences between 1,000 Hz and 100 Hz for RFD measured between 0–30 and 0–50 ms, which suggests sampling frequencies of ≥500 Hz may provide more valid results. Finally, Haff et al. (12) found greater reliability of RFD using predetermined time bands as opposed to peak RFD calculations, which were only reliable over a 20-milliseconds period. Given the influence of these methodological variations, it is recommended that practitioners follow best practice when standardizing methods and reporting IMTP variables (2).

Traditionally, assessment of the IMTP has been conducted using force plate systems, which often range in price from $2,000 to $20,000. This cost, coupled with the relative stationary nature

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Journal of Strength and Conditioning Research 38(1)/185–191

of the equipment, often exceed the budget or practical use requirements for both coaches and researchers. Load cells, however, provide a relatively small and inexpensive (<\$500) solution, which when paired with wireless technology provide a viable alternative that far surpasses the practicality of traditional force plate systems.

The practicality of a portable version of the IMTP using a single-axial load cell fixed to a steel platform has been shown to be highly reliable. James et al. (16) concluded that the load-cell system provided an acceptably valid measure of PF in adults compared with the criterion method using a force plate. However, using a chain with a fixed single-axial load cell may result in forces being applied in nonparallel directions to the load cell, resulting in potential inaccuracies in the measurement. Therefore, if a tangential force is applied during the IMTP, the resultant force of a fixed uniaxial load cell would be less than the total force produced. This phenomenon may explain the significantly different PF values and systematic underestimation of PF (14.1%; 229.05 N) in the portable load-cell IMTP reported by James et al. (16). Another limitation of the previous study involves the use of only 2 testing sessions to determine reliability of the experimental condition, which does not account for a possible learning effect. In addition, the load cell only allowed for sampling at 100 Hz, which is much lower than the recommended 1,000–2,500 Hz suggested for measuring RFD (7). Because both the measuring devices (load cell and force plate) and types of system (fixed bar and flexible chain) were changed simultaneously in the previous study (16), it is difficult to determine whether the differences in PF are due to the measuring device or type of system. Comparisons of a fixed bar vs. chain and a force plate vs. load cell may help isolate the cause of potential differences between systems. Therefore, the purpose of this study was to determine the reliability and validity of PF, RFD, and impulse characteristics during an IMTP using a chain as measured using a force plate (ChainFP) and freely moving load cell (ChainLC), compared with a criterion method IMTP using a fixed bar and measured using a force plate (BarFP).

Methods

Experimental Approach to the Problem

Subjects attended a familiarization session and 3 testing sessions exactly 7 days apart and at the same time of day (±1 hour). All subjects were informed of the risks of the study and gave written informed consent. The familiarization session was used for subjects to self-select their posture and determine the fixed-bar height and corresponding flexible-chain length to elicit an upright trunk with hip and knee angle of approximately 140–150° and 125–145°, respectively (2). These settings were recorded and replicated for all subsequent testing sessions. In each testing session, the subjects performed 6 trials total: 3 maximal efforts using the BarFP criterion condition, followed by 3 maximal efforts using the chain system, which measured ChainFP and ChainLC variables at the same time. Subjects were requested to maintain a normal dietary routine and refrain from exercise 24 hours before each testing session.

Subjects

Thirteen recreationally resistance-trained men (age: 26.9 ± 5.4 years, body mass: day 1 88.8 ± 22.1 kg, day 2 88.7 ± 22.4 kg, and day 3 88.8 ± 22.5 kg; height: 1.79 ± 0.6 m; resistance training experience: >6 months) volunteered to participate in this study. Sporting background for the subjects included weightlifting (snatch and clean and jerk), powerlifting, rugby sevens, track and field, and tennis. All subjects were fully informed of the risks involved and gave written informed consent. This experiment was approved by the Auckland University of Technology's Ethics Committee.

Procedures

Each subject performed a 10-minute standardized dynamic warm-up consisting of upper-body and lower-body exercises. The subjects then performed the BarFP test standing on a force plate with feet hip width apart, hips and knees bent, and upright torso to resemble the position of the start of the second pull of a clean (13). Subjects used a double overhand grip with hands secured using lifting straps just outside the legs. The height of the bar was measured during familiarization and kept consistent between all 3 subsequent testing sessions. The bar height for the BarFP test was converted to a corresponding chain length to reproduce the desired knee and hip angles for the ChainFP and ChainLC conditions. The subjects were instructed to pull "hard and fast" for 3 seconds with strong verbal encouragement throughout each maximal effort trial for both conditions (1). Each subject performed 3 maximal trials of the BarFP, followed by 3 maximal trials of the chain system measured simultaneously by a load cell (ChainLC) and force plate (ChainFP), each separated by 2 minutes of passive recovery. Subjects could use any pretension level they felt comfortable with and were permitted to repeat trials they felt were substandard. The trials were not randomized because of the time-consuming nature of the equipment setup. An identical testing protocol was applied during the second and third sessions.

Instrumentation. The BarFP trials were performed using a solid steel bar (length: 220.0 cm, diameter: 2.9 cm) fixed to a squat rack with 2 nonelastic ratchet straps, as shown in Figure 1. Height of the bar was adjustable in 2 and a half cm increments using the rack's J-shaped hooks. Force and moments in the x-, y-, and z-direction and center of pressure in the x- and y-direction were measured using a force plate (AccuPower, Advanced Mechanical Technology, Inc., Watertown, MA) sampling at 1,000 Hz. The resultant force was used for further analysis, rather than only the force in the z-direction. The 3 trials with the chain were performed using a solid steel straight T bar (length: 86.4 cm, diameter: 2.9 cm) with a chain attached to a single-axial load cell (MT501, Millennium Mechatronics, Auckland, NZ) sampling at 1,000 Hz. The load cell was attached to an immovable solid steel bar using a closed eye hook and a carabiner that allowed for the chain to rotate with the subject's line of pull, as shown in Figures 2 and 3. Therefore, the ChainFP and ChainLC values are from the same trial measured by a force plate and load cell concurrently.

All subject data were recorded using a custom-designed LabView program (National Instruments Corp., Austin, TX). Data were then imported into MATLAB (MathWorks, Inc., Natick, MA) for postprocessing and feature extraction. A 50-Hz, fourth-order lowpass Butterworth filter was selected after several lifts were plotted in the frequency domain using a fast Fourier transform, showing a clear separation between the actions of interest and occasional noise caused by the chain

Figure 1. Isometric midthigh pull setup for a fixed-bar system. The bar is fixed using an inverted cable rack attachment with ratchet straps keeping it secured from above.

system settling into place. Subject mass was removed from the force plate results and the resulting data were plotted to allow for a systematic method of manual onset detection, which is recommended by Maffiuletti et al. (21). The researcher identified the sudden onset of force (above the stable pretension level) in the load cell and force plate data to determine the onset of each lift and exclude any potential system lag. The mean RFD was calculated for 30, 60, 90, 100, 120, 150, and 200 milliseconds periods by dividing the difference in consecutive vertical force readings by the time interval between readings. Impulse at 100, 200, and 300 milliseconds was calculated using numerical integration using the area under the force-time curve from the onset of the pull. Peak force, peak RFD, and total impulse were also calculated for each pull.

Statistical Analyses

The mean and standard deviations (*SD*) were calculated for all results, and the 3 trials for all IMTP were averaged to obtain an individual mean for all force-time variables in each condition.

Figure 2. Isometric midthigh pull setup for a chain-based system. The bar is fixed just above the feet to simulate the attachment of the chain to the ground. This enables the force plate to measure the GRF at the same time the load cell measures the force through the chain.

Pairwise comparisons on log-transformed data were used to calculate intersession reliability (15) between all 3 testing sessions rather than a mean of all sessions. The data were log-

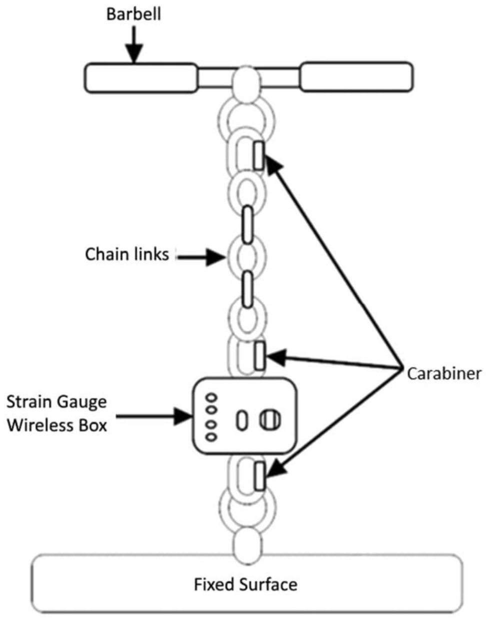

Figure 3. Breakdown of the components and setup of the chain-based isometric midthigh pull rig.

transformed to reduce any effects of nonuniformity of error (14). The percent change in mean (CM), coefficient of variation (CV), and intraclass correlation coefficient (ICC) were calculated and compared between sessions 1 and 2 and sessions 2 and 3 to determine any systematic bias from a learning effect. Acceptability and high cutoffs for ICC were considered ≥0.80 and ≥0.90, respectively, and the threshold for an acceptable and high CV was set at ≤10 and 5%, respectively (19). Ninety percent confidence intervals (90% CIs) were calculated for each variable. Repeated-measures general linear models were used to identify significant differences between all variables during the third testing session. A post hoc Bonferroni adjustment was used to identify where any differences occurred. Ordinary least-products regression was used to assess fixed and proportional bias of peak force for the ChainLC and ChainFP methods compared with the criterion (BarFP) using previously described methods (20). Fixed bias was present if the 95% confidence interval for the intercept (x) did not include 0, whereas proportional bias was present if the 95% confidence interval for the slope (y) did not include 1.0.

All descriptive statistics and the ordinary least-products regressions were calculated through Microsoft Excel 2016 (Microsoft, Corp., Redmond, WA) and reliability measures through a custom spreadsheet (15). The remaining data were analyzed using the Statistical Package for Social Sciences (IBM SPSS Statistics, Armonk, NY). Data are presented as mean ± *SD* and significance was set at $p \leq 0.05$.

Results

Rate of Force Development

The change in mean between sessions was larger for the BarFP (−29.8 to 87.8%) and ChainFP (−37.3 to 56.1%) conditions compared with the ChainLC condition (−11.8–10.4%), as shown in Tables 2–4. None of the RFD variables for the BarFP and ChainFP conditions demonstrated acceptable absolute (CV = 28.4–88.2%) or relative (ICC = −0.69–0.21) reliability between sessions 1 and 2 or 2 and 3. However, the ChainLC condition showed high relative reliability (ICC > 90%) between sessions 2 and 3 for peak RFD, RFD60, RFD90, and RFD100. The BarFP was significantly higher than the ChainFP and ChainLC conditions ($p < 0.05$) for all RFD variables except RFD30, but there were no differences between the ChainFP and ChainLC conditions. For RFD between 0 and 30 milliseconds, BarFP was significantly higher than both experimental conditions and ChainFP was higher than ChainLC ($p < 0.05$). The ChainLC condition showed smaller changes in the mean and CVs, as well as higher ICCs compared with the ChainFP and BarFP.

Impulse

The impulse measures showed a greater change in the mean across all 3 sessions for the BarFP and ChainFP (14.3–57.5%) compared with the ChainLC condition (2.5–7.3%). For all impulse variables, the BarFP and ChainFP conditions showed poor absolute and relatively reliability between sessions 1 and 2 (CV = 23.7–46.8%, ICC = 0.09–0.22) and sessions 2 and 3 (CV = 23.6–44.2%, ICC = 0.01–0.23). However, the ChainLC condition demonstrated high relative reliability (ICC = 0.90–0.93) between sessions 1 and 2 for impulse at 100, 200, and 300 milliseconds. There were no significant differences between conditions for impulse at 100 milliseconds or total impulse ($p > 0.05$). Impulse at 200 and 300 milliseconds was significantly lower in the experimental conditions compared with the criterion ($p < 0.05$), but there was no significant difference between ChainFP and ChainLC conditions. In general, impulse measures for the ChainLC condition had lower changes in the mean and CVs, as well as higher ICCs, than the ChainFP and criterion condition.

Peak Force

There were relatively small changes in the mean PF values between sessions for each condition, ranging from −1.5 to 5.2%, as shown in Tables 1–3. The PF was also highly reliable for each condition: BarFP (CV = 6.3–6.9%, ICC = 0.96–0.97), ChainFP (CV = 4.9–8.3%, ICC = 0.94–0.98), and ChainLC (CV = 4.6–7.9%, ICC = 0.94–0.98). Post hoc analysis indicated that the BarFP PF was significantly higher than the ChainFP by 4.8% ($p < 0.05$), but not the ChainLC ($p = 0.153$), which was 3.4% lower. The PF for the ChainLC condition was also significantly higher than the ChainFP by 1.4% ($p < 0.001$). The least-products regression showed no proportional or fixed bias for either the ChainFP or the ChainLC when compared to the criterion method (Table 4). In general, there were greater changes in the mean, larger CVs, and lower ICCs between sessions 2 and 3 than sessions 1 and 2.

Discussion

The purpose of this study was to establish the intersession reliability of a chain-based IMTP system using a freely moving load cell and force platform and determine the validity compared with the criterion method consisting of a traditional IMTP using a fixed bar and force plate. The flexible-chain IMTP was measured using a force platform and rotating load cell to determine differences in force-time characteristics between the 2 systems. The main findings were (a) no RFD or impulse measure were found to achieve acceptable intersession reliability across all methodological approaches; (b) PF was found reliable across all methods and testing occasions, with CVs ranging from 4.6 to 8.3%, ICCs from 0.94 to 0.98, and the least variability in the ChainLC condition; (c) neither the ChainFP nor ChainLC showed fixed or proportional bias compared with the criterion method, but the ChainFP method significantly underrepresented PF (−114.7 N, 3.4%). It seems that the ChainLC method is equally reliable and valid compared with the criterion force platform method, although more portable and cost efficient.

The finding of low intersession reliability for RFD and impulse (CVs: 10.2–87.6%; ICCs: −0.69–0.93) was similar to previous studies using a chain and load cell (16) or bar and force platform (4,23). For example, James et al. (16) reported ICCs ranging from −0.31 to 0.10 and CVs ranging from 17.3 to 73.4% for RFD variables using a fixed load cell, which measures the vertical axis exclusively but was a comparable setup to the chain-based force platform method in the current study. One cause for the variability in these measures can likely be attributed to the variety of methods used to determine the initiation of the pull (6,21) or quantify RFD (12). For example, several methods to determine the initiation of the pull for RFD and impulse measures have been reported (6), although the

Table 1

Between-session reliability of force, RFD, and impulse measures for the BarFP condition.*

	Mean ± *SD*			Change in the mean (%) (90% CI)		CV (90% CI)		ICC (90% CI)	
Variables	**Day 1**	**Day 2**	**Day 3**	**Days 1–2**	**Days 2–3**	**Days 1–2**	**Days 2–3**	**Days 1–2**	**Days 2–3**
Peak force (N)	2,474.28 ± 657.01	2,435.1 ± 674.84	2,489.21 ± 750.92	−1.5 (−6.0 to 3.2)	2.2 (−2.3 to 6.9)	6.9 (5.2 to 10.6)	6.3 (4.7 to 10.0)	0.96 (0.89 to0.98)	0.97 (0.91 to 0.99)
Peak RFD (N·s^{-1})	11,617.7 ± 3,773.2	8,452.9 ± 3,637.3	13,269.9 ± 2,909.7	−28.6 (−44.7 to 7.6)	60.6 (28.8 to 100.2)	44.4 (32.0 to 74.5)	35 (25.2 to 59.3)	−0.28 (−0.66 to 0.20)	−0.13 (−0.60 to 0.37)
RFD 0–30 ms (N·s^{-1})	2,845.17 ± 1825	2,705.6 ± 2,245.2	3,963.32 ± 1,694.7	−15.4 (−39.8 to 18.7)	66.7 (4.9 to 165.1)	62.5 (44.3 to 108.7)	88.2 (60.5 to 166.7)	0.21 (−0.28 to 0.61)	−0.45 (−0.81 to 0.05)
RFD 0–60 ms (N·s^{-1})	4,512.36 ± 2,546.3	3,980 ± 2,921	6,183.23 ± 2,292.6	−20.9 (−43.9 to 11.6)	77.1 (16.4 to 169.4)	63.4 (44.9 to 110.5)	77.2 (53.4 to 142.9)	0.19 (−0.30 to 0.59)	−0.28 (−0.71 to 0.23)
RFD 0–90 ms (N·s^{-1})	5,467.25 ± 2,681.2	4,623.2 ± 2,962.9	7,607.84 ± 2,538.2	−21.8 (−44.4 to 10.0)	80.1 (23.0 to 163.8)	62.9 (44.6 to 109.4)	68.3 (47.6 to 124.1)	0.06 (−0.41 to 0.50)	−0.27 (−0.69 to 0.25)
RFD 0–100 ms (N·s^{-1})	5,605.93 ± 2,599.2	4,707.2 ± 2,862.5	7,888.17 ± 2,523.3	−21.3 (−43.5 to 9.5)	80.5 (26 to 158.6)	60.4 (42.9 to 104.7)	63.3 (44.3 to 113.9)	0.02 (−0.44 to 0.47)	−0.25 (−0.68 to 0.26)
RFD 0–120 ms (N·s^{-1})	5,766.85 ± 2,444.8	4,707.7 ± 2,553.7	8,204.49 ± 2,441.5	−22.1 (−42.5 to 5.6)	84.5 (34.0 to 153.9)	54.5 (38.9 to 93.3)	54.6 (38.5 to 96.5)	−0.03 (−0.48 to 0.44)	−0.23 (−0.67 to 0.28)
RFD 0–150 ms (N·s^{-1})	5,935.77 ± 2,247.1	4,535.1 ± 2020.1	8,256.17 ± 2,198.7	−25.3 (−42.5 to 3.0)	87.8 (42.2 to 148.0)	45.3 (32.6 to 76.2)	46.1 (32.8 to 80.1)	−0.06 (−0.51 to 0.41)	−0.39 (−0.77 to 0.12)
RFD 0–200 ms (N·s^{-1})	8,218.73 ± 1950.8	4,234 ± 1,512.2	7,538.67 ± 1,673.9	−29.8 (−43.4 to 13.1)	79.4 (42.7 to 125.4)	35.8 (26.0 to 59.0)	36.6 (26.3 to 62.2)	0.07 (−0.40 to 0.51)	−0.44 (−0.80 to 0.06)
Impulse 0–100 ms (Ns)	67.08 ± 29.46	45.4 ± 12.93	66.44 ± 30.16	−27.3 (−44.4 to 4.8)	38.6 (7.8 to 78.2)	46.8 (33.7 to 79.0)	40.9 (29.2 to 70.1)	−0.23 (−0.62 to 0.25)	0.01 (−0.50 to 0.48)
Impulse 0–200 ms (Ns)	200.12 ± 71.21	138.27 ± 39.36	221.95 ± 70.69	−28.3 (−44.0 to 8.4)	57.5 (30.4 to 90.3)	42.1 (30.4 to 70.3)	29.4 (21.3 to 49.1)	−0.45 (−0.75 to 0.01)	0.04 (−0.47 to 0.50)
Impulse 0–300 ms (Ns)	378.79 ± 117.99	260.48 ± 66.16	417.2 ± 110.99	−29.3 (−43.4 to 11.9)	57.1 (33.7 to 84.6)	37.1 (26.9 to 61.3)	24.6 (17.9 to 40.6)	−0.47 (−0.76 to 0.01)	0.03 (−0.48 to 0.49)
Total impulse (Ns)	10,348.8 ± 3,053.3	7,728 ± 1,116.5	9,614.91 ± 2,544.7	−23.6 (−35.9 to 9.1)	22.9 (3.7 to 45.6)	28.3 (20.7 to 45.9)	26.1 (18.9 to 43.2)	−0.22 (−0.62 to 0.26)	−0.03 (−0.53 to 0.45)

*RFD = rate of force development; BarFP = fixed bar with a force plate; CI = confidence interval; CV = coefficient of variation; ICC = intraclass correlation coefficient.

Table 2

Between-session reliability of force, RFD, and impulse measures for the ChainFP condition.*

	Mean ± *SD*			Change in the mean (%) (90% CI)		CV (90% CI)		ICC (90% CI)	
Variables	**Day 1**	**Day 2**	**Day 3**	**Days 1–2**	**Days 2–3**	**Days 1–2**	**Days 2–3**	**Days 1–2**	**Days 2–3**
Peak force (N)	2,260.72 ± 593.14	2,273.3 ± 605.26	2,374.52† ± 662.03	0.6 (−2.6 to 3.9)	5.1 (−0.9 to 11.4)	4.8 (3.6 to 7.3)	8.3 (6.1 to 13.1)	0.98 (0.94 to 0.99)	0.94 (0.84 to 0.98)
Peak RFD (N·s^{-1})	10,707.9 ± 5,230.1	7,205 ± 2,737.6	10,685.27† ± 3,240.9	−28.5 (−46.6 to 4.3)	41.6 (8.1 to 85.4)	51.8 (37.0 to 88.2)	44.5 (31.7 to 76.9)	−0.1 (−0.53 to 0.37)	−0.45 (−0.77 to 0.06)
RFD 0–30 ms (N·s^{-1})	3,854.02 ± 2,706.9	2,550 ± 1721.4	3,015.16† ± 1,338.3	−33.4 (−55.9 to 0.8)	20.2 (−15.0 to 70.0)	80.7 (56.4 to 145.2)	60.5 (42.4 to 108.2)	−0.59 (−0.83 to 0.18)	−0.35 (−0.75 to 0.16)
RFD 0–60 ms (N·s^{-1})	5,758.13 ± 3,800.2	3,504.7 ± 2,189.4	4,683.92† ± 2,101.6	−37.3 (−59.6 to 2.6)	34.1 (−9.5 to 98.7)	87.6 (60.8 to 159.4)	70.9 (49.3 to 129.6)	−0.67 (−0.86 to 0.31)	−0.57 (−0.87 to 0.10)
RFD 0–90 ms (N·s^{-1})	6,086.59 ± 3,357	3,840.8 ± 2027.6	5,759.94† ± 2,499.2	−33.4 (−54.8 to 1.8)	43.2 (−1.6 to 108.4)	74.2 (52.1 to 131.8)	66.9 (46.7 to 121.3)	−0.69 (−0.87 to 0.34)	−0.75 (−0.95 to 0.37)
RFD 0–100 ms (N·s^{-1})	5,989.55 ± 3,053.7	3,895.8 ± 1941.7	5,972.11† ± 2,486.6	−31.6 (−52.3 to 1.9)	45.3 (0.8 to 109.5)	67.5 (47.7 to 118.6)	64.7 (45.2 to 116.8)	−0.67 (−0.86 to 0.30)	−0.77 (−0.96 to 0.40)
RFD 0–120 ms (N·s^{-1})	5,697.9 ± 2,509.7	3,877.4 ± 1703.3	6,217.88† ± 2,293.5	−28.8 (−47.9 to 2.8)	53.3 (14.5 to 105.1)	56.2 (40.1 to 96.6)	48.8 (34.6 to 85.2)	−0.57 (−0.82 to 0.15)	−0.35 (−0.75 to 0.16)
RFD 0–150 ms (N·s^{-1})	5,495.14 ± 2083.4	3,836.3 ± 1,525.8	6,246.81† ± 1920.4	−27.5 (−44.4 to 5.6)	56.1 (21.6 to 100.4)	46.1 (33.2 to 77.6)	40.6 (29.0 to 69.5)	−0.51 (−0.78 to 0.06)	−0.34 (−0.74 to 0.17)
RFD 0–200 ms (N·s^{-1})	5,544.09 ± 2035.3	3,758.7 ± 1,367.3	6,005.96† ± 1,544.4	−29.4 (−44.1 to 10.8)	53.7 (28.0 to 84.6)	39.6 (28.7 to 65.9)	28.4 (20.5 to 47.3)	−0.41 (−0.73 to 0.06)	−0.11 (−0.59 to 0.38)
Impulse 0–100 ms (Ns)	57.52 ± 23.87	43.44 ± 9.79	62.22† ± 26.92	−19.0 (−36.2 to 2.9)	33.2 (1.8 to 74.2)	40.8 (29.5 to 67.9)	44.2 (31.5 to 76.4)	−0.1 (−0.53 to 0.38)	−0.16 (−0.63 to 0.34)
Impulse 0–200 ms (Ns)	171.75 ± 61.85	127.75 ± 30.21	192.04† ± 54.87	−21.3 (−37.2 to 1.4)	46.6 (20.9 to 76.2)	38.1 (27.7 to 63.2)	29.3 (21.2 to 48.9)	−0.18 (−0.59 to 0.30)	−0.23 (−0.67 to 0.28)
Impulse 0–300 ms (Ns)	325.76 ± 106.44	244.13 ± 53.97	361.45† ± 86.02	−21.3 (−35.5 to 3.9)	43.9 (23.2 to 68.1)	33.1 (24.1 to 54.2)	23.6 (17.2 to 38.9)	−0.09 (−0.53 to 0.38)	−0.19 (−0.64 to 0.32)
Total impulse (Ns)	9,224.39 ± 2,695	7,870 ± 1,501.7	9,574.51† ± 2,606.4	−14.3 (−26.2 to 0.6)	23.5 (1.9 to 49.7)	23.7 (17.4 to 38.0)	30 (21.7 to 50.3)	0.23 (−0.26 to 0.62)	−0.1 (−0.58 to 0.39)

*RFD = rate of force development; CI = confidence interval; CV = coefficient of variation; ICC = intraclass correlation coefficient.
†Significantly lower than the criterion condition ($p < 0.05$).

visual onset method is considered the gold standard (21) and thus was the method of choice for this study. Haff et al. (12) established greater RFD reliability using predetermined time bands ranging from 0–30 to 0–250 milliseconds (ICC > 0.95, CV $< 4\%$) compared with using average RFD (ICC = 0.74), although this approach was used in the current study with limited success. In general, RFD and impulse measures did not show acceptable intersession reliability for any of the methodological approaches used. Given that acceptable reliability and validity of a method must be achieved before it is determined relevant, discussion from this point forward will focus on the reliability and validity of the experimental approaches used for measuring PF.

Peak force showed acceptable reliability for all 3 approaches across all sessions in the current study. Similarly, IMTP PF measured using a fixed bar and force plate have been reported to have high reliability within-sessions and between-sessions (4,11,17,18,23). In this study, the BarFP method (CM = 1.9%, CV = 6.6%, ICC = 0.97) and ChainFP method (CM = 2.8%, CV = 6.6%, ICC = 0.96) achieved similar reliability, suggesting a chain-based system is equally reliable as a fixed-bar system. However, the load cell's ability to rotate with the subject's line of pull may be a more valid method, as evidenced by the ChainLC results in the current study. The implications of this finding are that the chain-based approach may be more practical for coaches or researchers working with large groups, or subjects who vary in height, without sacrificing reliability of measures. Furthermore, the load cell used for portable IMTP setups should not be fixed, which allows for more accurate force outputs.

One limitation of the current study was the self-selected level of pretension before beginning each trial. Several authors have suggested using minimal pretension (12) or just enough to pull the slack out of the system (2) to reduce changes in joint angle on initiation of the pull. This methodological factor may help explain the lack of reliability in the time-specific metrics, such as RFD and impulse. For example, Dos'Santos et al. (8) reported that a greater hip angle, and therefore more pretension and a higher "body mass," may have contributed to differences in RFD and time-based force metrics. In addition, Guppy et al. (9) reported unreliable RFD values for 4 different IMTP positions, which may have been a result of varying knee and hip angles and therefore pretension. Further research should aim to adhere to the recommendation of using just enough pretension to remove any slack from the system, but no more than is needed to achieve a stable baseline force (21).

This study was the first to examine the between-session reliability of a flexible-chain IMTP approach using at least 3 testing sessions, which is fundamental in determining whether learning effects from repetitive exposure to the activity are present (22). We found that the CVs and ICCs of this study (CM = 2.8%, CV = 6.3%, ICC = 0.96) were comparable to other studies using portable load-cell versions of the IMTP. For example, high within-session reliability of PF in youth males (CV = 6.0%, ICC = 0.91) (25) and between-session reliability of PF in adults (CV = 3.1%, ICC = 0.96) (16) have been previously reported. Based on our findings, it seems that biological and technological variation is minimal, using a chain is equally reliable for assessing PF compared with a fixed bar, and a load cell shows similar reliability as a force plate which enables practitioners to use this proposed method without compromising accuracy of results.

Table 3

Between-session reliability of force, RFD, and impulse measures for the ChainLC condition.*

	Mean ± *SD*			Change in the mean (%) (90% CI)		CV (90% CI)		ICC (90% CI)	
Variables	**Day 1**	**Day 2**	**Day 3**	**Days 1–2**	**Days 2–3**	**Days 1–2**	**Days 2–3**	**Days 1–2**	**Days 2–3**
Peak force (N)	2,286.71 ± 596.83	2,294.6 ± 600.85	2,407.9 ± 703.64	0.4 (−2.7 to 3.7)	5.2 (−0.6 to 11.2)	4.6 (3.5 to 7.1)	7.9 (5.9 to 12.6)	0.98 (0.94 to 0.99)	0.94 (0.85 to 0.98)
Peak RFD (N·s^{-1})	11,578.5 ± 7,121.8	12,119 ± 5,660.6	10,604.95† ± 4,646	5.3 (−11.2 to 24.8)	−10.0 (−19.4 to 0.4)	27.6 (20.2 to 44.7)	16.1 (11.8 to 26.1)	0.73 (0.38 to 0.89)	0.91 (0.75 to 0.97)
RFD 0–30 ms (N·s^{-1})	2,890.18 ± 1753.5	2,858 ± 1980.2	2,307.58†,‡ ± 1,266.9	−1.9 (−28.1 to 33.8)	−11.5 (−27.9 to 8.7)	55.9 (39.8 to 96.0)	32.3 (23.3 to 54.3)	0.22 (−0.27 to 0.61)	0.63 (0.27 to 0.86)
RFD 0–60 ms (N·s^{-1})	5,037.42 ± 3,071.3	5,190.7 ± 3,623	4,195.29† ± 2,346	2.4 (−26.0 to 41.9)	−11.8 (−24.9 to 3.5)	59.4 (42.2 to 102.6)	24.4 (17.8 to 40.4)	0.35 (−0.13 to 0.70)	0.86 (0.65 to 0.95)
RFD 0–90 ms (N·s^{-1})	6,342.64 ± 3,826.5	6,671.4 ± 4,066.3	5,726.64† ± 3,001.7	7.4 (−20.6 to 45.3)	−9.2 (−19.7 to 2.7)	54 (38.6 to 92.4)	18.3 (13.4 to 29.8)	0.42 (−0.05 to 0.73)	0.91 (0.77 to 0.97)
RFD 0–100 ms (N·s^{-1})	6,547.88 ± 3,864.7	6,912.6 ± 4,000.2	6,059.30† ± 3,070.8	8.5 (−19.0 to 45.4)	−8.3 (−18.1 to 2.7)	52 (37.2 to 88.6)	16.7 (12.2 to 27.0)	0.41 (−0.08 to 0.74)	0.92 (0.77 to 0.97)
RFD 0–120 ms (N·s^{-1})	6,633.97 ± 3,614.3	7,035.6 ± 3,633.5	6,386.87† ± 2,975.1	9.5 (−16.2 to 43.3)	−8.2 (−27.7 to 16.7)	46.8 (33.6 to 78.9)	38.6 (27.7 to 65.9)	0.44 (−0.02 to 0.75)	0.55 (0.09 to 0.81)
RFD 0–150 ms (N·s^{-1})	6,193.53 ± 2,839.9	6,646.5 ± 2,727.8	6,262.38† ± 2,516	10.4 (−11.7 to 38.1)	−5.6 (−23.1 to 15.8)	37.7 (27.4 to 62.5)	32.3 (23.3 to 54.3)	0.47 (0.01 to 0.76)	0.55 (0.10 to 0.81)
RFD 0–200 ms (N·s^{-1})	5,271.06 ± 1914.3	5,666 ± 1,664.7	5,450.31† ± 1838.8	9.4 (−6.9 to 28.7)	−5.2 (−19.8 to 12.0)	26.1 (19.1 to 42.1)	25.5 (18.5 to 42.2)	0.55 (0.12 to 0.80)	0.55 (0.09 to 0.81)
Impulse 0–100 ms (Ns)	59.15 ± 23.68	61.55 ± 26.56	58.24† ± 24.56	2.5 (−5.7 to 11.3)	−4.2 (−26.3 to 24.7)	12.6 (9.3 to 19.6)	43.2 (30.8 to 74.5)	0.93 (0.82 to 0.97)	0.28 (−0.24 to 0.66)
Impulse 0–200 ms (Ns)	181.62 ± 60.37	192.88 ± 69.67	183.93† ± 68.06	5.5 (−2.5 to 14.2)	−5.1 (−23.2 to 17.2)	12 (8.9 to 18.8)	33.4 (24.1 to 56.4)	0.9 (0.75 to 0.96)	0.38 (−0.12 to 0.72)
Impulse 0–300 ms (Ns)	329.94 ± 96.06	347.3 ± 109.1	336.22† ± 113.97	4.6 (−2.3 to 12.0)	−4.3 (−20.6 to 15.4)	10.2 (7.6 to 15.9)	29 (21.0 to 48.4)	0.91 (0.77 to 0.96)	0.43 (−0.06 to 0.75)
Total impulse (Ns)	8,331.42 ± 2,323	8,714.8 ± 1996.8	9,389.39† ± 2,835.1	6.7 (−2.2 to 16.3)	7.3 (−10.9 to 29.2)	13.3 (9.9 to 20.8)	28.9 (20.9 to 48.2)	0.08 (0.53 to 0.92)	0.01 (−0.49 to 0.48)

*RFD = rate of force development; ChainLC = chain measured with a load cell; CI = confidence interval; CV = coefficient of variation; ICC = intraclass correlation coefficient.

†Significantly lower than the criterion condition ($p < 0.05$).

‡Significantly lower than the ChainFP condition ($p < 0.05$).

Table 4

Ordinary least-products regression for the ChainLP and ChainLC compared with the BarFP condition.*

R^2		Slope (95% CI)		Intercept (95% CI)	
ChainFP	ChainLC	ChainFP	ChainLC	ChainFP	ChainLC
0.90	0.90	1.024 (0.959 to 1.090)	1.034 (0.968 to 1.099)	108.474 (−47.437 to 264.384)	59.858 (−99.111 to 218.826)

*ChainLP = chain measured with a force plate; ChainLC = chain measured with a load cell; BarFP = fixed bar with a force plate; CI = confidence interval.

Practical Applications

To the best of our knowledge, this was the first study to use a load cell attached in a flexible manner to assess force-time variables in the resultant line of pull from the subject, as well as use 3 testing sessions to determine any learning effect of a chain-based IMTP. None of the RFD or impulse measurements achieved acceptable intersession reliability across any of the testing conditions. Peak force was reliable with all 3 testing conditions, although the ChainLC method produced the least variability. Furthermore, the ChainLC was valid compared with the criterion BarFP method, whereas the ChainFP method significantly underrepresented PF, likely because of the force plate's measurement of vertical forces despite a chain that moves with the subject's line of pull. Therefore, the ChainLC is a valid and reliable method to assess PF in healthy adult men and offers a more portable and cost-effective alternative for athletic settings compared with the traditional IMTP with a force plate in a laboratory.

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