Does a linear position transducer placed on a stick and belt provide sufficient validity and reliability of countermovement jump performance outcomes?

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ABSTRACT: Manufacturers recommend that linear position transducers (LPTs) should be placed on the side of a barbell (or wooden dowel) to measure countermovement jump (CMJ) height, but the validity and reliability of this placement have not been compared to other attachment sites. Since this recommended attachment site is far from the centre of mass, a belt attachment where the LPT is placed between the feet may increase the validity and reliability of CMJ data. Thirty-six physical education students participated in the study (24.6 ± 4.3 years; 177.0 ± 7.7 cm; 77.2 ± 9.0 kg). Parameters from the two LPT attachments (barbell and belt) were simultaneously validated to force plate data, where the nature of bias was analysed (systematic vs random). The within-session and between-session reliability of both attachment sites were compared to force plate data using a test-retest protocol of two sets of 5 CMJs separated by 7 days. The LPT provided highly reliable and valid measures of peak force, mean force, mean power, and jump height, where the bias was mostly systematic ($r^2 > 0.7$; ICC > 0.9). Peak velocity, mean velocity, and peak power were in very good agreement with the force plate and were highly reliable ($r^2 > 0.5$; ICC > 0.7). Therefore, both attachment sites produced similar results with a systematic bias compared to force plate data. Thus, both attachment sites seem to be valid for assessing CMJs when the measuring tool and site remain consistent across measurements. However, if LPT data are to be compared to force plate data, recalculation equations should be used.

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INTRODUCTION

Unloaded countermovement jumps (CMJs) are not only used in training, but also function as a traditional test of lower limb power output, which is highly relevant in sports such as track and field [1–3], basketball [4, 5], football [6, 7], and others [8]. Historically, coaches and scientists usually treated jump height as the primary variable of interest and as an indicator of explosive strength [9]. However, as technology continues to develop, more recent studies have indicated how useful other parameters can be, such as peak or mean force, velocity, and power output [1, 10]. Additionally, information about the rate of force development and the time to peak force, velocity, and power may be desired [11, 12]. However, obtaining and using the previously mentioned parameters requires a reliable and valid method of measurement and calculation.

Naturally, force plates are considered the gold standard for measuring contact forces and calculating jump height from the force impulse as a double integration of force [13]. However, since force plates are often expensive laboratory-based pieces of equipment, other cheaper and more portable devices have been developed to measure (Vertec) or calculate jump height from flight time (Optojump, accelerometer-based devices such as Myotest, contact mats). Although these aforementioned tools are commonly used to assess jump performance, they exhibit either systematic [14–17] or non-systematic (random) bias [18–20]. Additionally, the advantage of the force plate is the capability to calculate accurately force impulse and instantaneous velocity and power subsequently, which may not be possible with devices that estimate, rather than directly measure, such variables.

Of the aforementioned tools, LPTs are designed to directly measure the instantaneous displacement of a fixed point, effectively making them a popular choice for measuring displacement in exercises such as the CMJ. From the change in displacement and time, LPTs can also be used to assess other explosive strength parameters [21]. Due to their applicability and popularity, many studies have assessed the validity and reliability of LPTs in squat jumps, loaded CMJs, the bench press, and other exercises [16, 22–25]. However, in most of these exercises, the LPT manufacturers advise users to attach the end of the cable to a barbell or light stick in place of a barbell. Assuming that a standard barbell or wooden dowel can extend up to

1 meter on either side of an athlete, attaching a measuring device (such as an LPT) that far from the centre of mass may result in skewed or unreliable data, especially if an athlete does not perform an exercise in a perfect linear direction about the z-, y-, or x-axis. Rather than attaching the LPT superior and lateral to the centre of mass, it is possible that attaching it to or near the waist [26] may result in more reliable and valid data during CMJ testing.

Therefore, we decided to test the reliability and validity of a commercially available linear position transducer (LPT) during unloaded CMJs using two attachment points simultaneously: one according to the manufacturer's guidelines near the edge of a wooden dowel, and one closer to the centre of mass via an adjustable canvas belt. As such, we hypothesized that there would be a systematic bias between jump height measured at both LPT attachments sites compared to jump height measured via a force plate. Furthermore, we hypothesized that the waist attachment site would be more reliable than the wooden dowel attachment site due to fewer degrees of freedom in terms of movement.

MATERIALS AND METHODS

Experimental design

Participants completed CMJs on three different occasions, each separated by one week. During the first occasion, participants were familiarized with the testing procedures. After one week, the participants performed two sets of five CMJs, and the process was repeated one week later. Participants performed all jumps on a force plate with an LPT attached to the waist and another LPT attached to a wooden dowel that was held posterior to the head in a high-bar squat position. The analysed parameters were jump height and peak and mean concentric force, velocity, and power. Inter-session and within-session reliability was analysed to assess the reliability of both LPT attachment sites in comparison with a force plate. Concurrent validity of LPT data was compared with the force plate, which served as the gold standard.

Participants

Thirty-six healthy university sport science students participated in the study (24.6 ± 4.3 years; 177. ± 7.7 cm; 77.2 ± 9.0 kg). The project was approved by the faculty ethical committee. Each participant was informed about the goal of the study and the procedures. Participants were free to withdraw from the experiment at any moment without penalty. Those who voluntarily agreed to participate in the study signed written consent.

Procedures

Each participant started each session with a standard warm-up protocol. This protocol consisted of 5 minutes jogging, 5 minutes of dynamic stretching, and two sets of three non-measured CMJs performed at maximal intensity. A 2-minute interval of passive rest separated these sets. Participants began their measured trials after 2 minutes of rest.

Each measured set consisted of 5 consecutive CMJs. For each repetition, subjects were instructed to include a countermovement with self-selected depth and speed, an explosive jump “as high and as fast as possible”, a soft landing, and to return to the standing position for approximately 2 seconds before initiating the countermovement of the next repetition. After completing five jumps, participants were given 3 minutes of active rest (i.e. walking around the laboratory) before completing the second set.

The participants stood on two force plates (Kistler 6384, Winterthur, Switzerland; 1000 Hz) that were positioned side-by-side with approximately a 10 cm gap where one of the LPTs rested on the floor. The measured trial was simultaneously recorded with two independent LPTs (GymAware Power Tool, Kinetic Performance Technologies, Canberra, Australia). One of the LPTs was placed between the force plates and was attached to the belt fixed on the waist of the participant. The second LPT was placed on the side of the force plate and was attached to the wooden dowel, which was placed on the participants' shoulders. Participants held the bar with both hands. Participants were instructed to jump as high as possible when hearing the command “go”.

Each participant's data were stored for further analysis after completing the session. The LPT of the current study measures the total displacement of its cable in response to changes in the barbell position and incorporates an angle sensor that accounts for motion in the horizontal direction during predominantly vertical displacement measurements. The LPT software later accounts for the total distance and angle, and using basic trigonometry, provides a resultant vertical displacement. Instantaneous velocity was determined as the change in barbell position with respect to time, which is also provided by the LPT software. Data obtained from the LPT were transmitted via Bluetooth to a tablet (iPad, Apple Inc., California, USA) using the GymAware v2.4.1 app, and to the online cloud before being exported to Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) and prepared for further analysis. The data from the force plate were exported from the original software (Bioware, Kistler, Winterthur, Switzerland) and further processed in MATLAB (R2019, MathWorks Inc., Natick, Massachusetts, USA). The instantaneous velocity v(t) was calculated using the integration of force:

$$v(t) = \int_{t_0}^{t} \frac{(F_v(t) - mg)}{m} dt$$

where $F_v(t)$ is the instantaneous vertical ground reaction force at time t, m is the participant's body mass, g is gravitational acceleration, and t_0 is the time of the last sample before F_v fell below 95% of the participant's body weight in newtons. Instantaneous power output was calculated as a product:

$$P(t) = F_v(t) \times v(t)$$

where $P(t)$ is instantaneous power, $F_v(t)$ is the vertical ground reaction force, and $v(t)$ is estimated instantaneous velocity. Instantaneous displacement was calculated as double integration of force divided by mass. The instant of switch of eccentric to concentric phase was when instantaneous velocity reached a positive value. Average concentric force (MF), velocity (MV), and power (MP) were calculated as the mean of instantaneous values between the eccentric/concentric switch and the end of the take-off. Jump height from the force impulse (IJH) was calculated from the equation:

$$IJH = \frac{V_{TO}^2}{2g}$$

where V_{TO} is the instantaneous velocity at take-off, and g is the gravitational acceleration. Additionally, jump height was also obtained from flight time (FJH) using the following equation:

$$FJH = \frac{g(t_{TD} - t_{TO})^2}{8}$$

where g is gravitational acceleration, t_{TD} is the time of touch-down, and t_{TO} time of take-off.

Rate of force development (RFD) was calculated as a ratio of peak force (PF) and time from eccentric/concentric switch to time of peak force achievement (time to peak force).

Statistical analysis

An Excel spreadsheet [27] was used to assess the validity and systematic or random bias. Values obtained from the force plate served as a criterion to which data from both LPT attachment sites were compared. First, the distribution of bias was checked to determine whether data needed to be log-transformed (no parameters needed to be log-transformed except RFD from both LPT attachment sites). The level of confidence was set to 95%, and the standardized smallest important difference was set to 0.2 [28].

Bias was calculated as the difference between criterion and practical means, and standardized bias was computed as the bias divided by criterion SD. A modified Cohen's d scale was used to interpret the magnitude of difference for trained individuals: < 0.2 trivial; 0.2–0.6 small; 0.6–1.2 moderate; 1.2–2.0 large; 2.0–4.0 very large; > 4.0 extremely large [27, 29].

TABLE 1. The average and standardized bias of performance outputs from the force plate and two placement of linear position transducers.

Outputs	LPT position	force plate (mean ± SD)	LPT (mean ± SD)	bias (LCL; UCL)	Standardized bias (LCL; UCL)
MF [N]	**belt**	1417 ± 257	1589 ± 335	172 (161; 184)	0.67 (0.63; 0.72)
	stick		1624 ± 343	208 (195; 220)	0.81 (0.76; 0.86)
PF [N]	**belt**	1795 ± 337	2141 ± 499	345 (321; 370)	1.02 (0.95; 1.10)
	stick		2242 ± 544	447 (419; 474)	1.33 (1.24; 1.41)
MP [W]	**belt**	1945 ± 476	2652 ± 727	706 (675; 738)	1.48 (1.42; 1.55)
	stick		2845 ± 800	900 (861; 938)	1.89 (1.81; 1.97)
PP [W]	**belt**	3523 ± 825	4826 ± 1477	1304 (1224; 1383)	1.58 (1.48; 1.68)
	stick		4852 ± 1333	1329 (1251; 1408)	1.61 (1.52; 1.71)
MV [m/s]	**belt**	1.49 ± 0.14	1.82 ± 0.19	0.33 (0.32; 0.34)	2.27 (2.18; 2.36)
	stick		1.95 ± 0.25	0.46 (0.44; 0.47)	3.16 (3.06; 3.26)
PV [m/s]	**belt**	2.55 ± 0.23	3.08 ± 0.33	0.53 (0.51; 0.55)	2.29 (2.21; 2.37)
	stick		3.17 ± 0.34	0.62 (0.60; 0.64)	2.70 (2.61; 2.79)
jump height [cm] (force impulse)	**belt**	29.9 ± 6	38.3 ± 7.0	8.4 (8.2; 8.7)	1.41 (1.37; 1.45)
	stick		39.7 ± 7.4	9.8 (9.5; 10.1)	1.64 (1.59; 1.68)
jump height [cm] (flight time)	**belt**	31.1 ± 6.5	38.3 ± 7.0	7.2 (7.0; 7.4)	1.11 (1.07; 1.15)
	stick		39.7 ± 7.4	8.5 (8.3; 8.8)	1.32 (1.28; 1.36)
RFD $[N.s^{-1}.kg^{-1}]$	**belt**	79.6 ± 62.5	58.0 ± 21.6	-21.6 (-26.5; -16.7)	-0.35 (-0.42; -0.27)
	stick		67.2 ± 23.7	-12.4 (-17.5; -7.2)	-0.20 (-0.28; -0.12)
RFD $[N.s^{-1}.kg^{-1}]$*	**belt**	66.2 ×/÷ 1.82	54.5 ×/÷ 1.422[a]	0.837 (0.793; 0.884)[b]	-0.30 (-0.39; -0.21)
	stick		63.3 ×/÷ 1.414[a]	0.957 (0.904; 1.014)[b]	-0.07 (-0.17; -0.02)

LPT = linear position transducers, LCL = lower confidence limit, UCL = upper confidence limit, * denotes log-transformed data; [a] geometric mean reported with standard deviation as a factor; [b] bias is reported as a factor. MF = mean force, PF = peak force, MP = mean power, PP = peak power, MV = mean velocity, PV = peak velocity, RFD = rate of force development.

TABLE 2. The systematic and random bias of belt and stick linear position transducer attachments in comparison to force plate. All values are reported as means (LCL – lower confidence limit; UCL – upper confidence limit).

Outputs	LPT position	intercept	slope	TEE	Standardized TEE	r	r^2
MF	**belt**	272 (234; 309)	0.721 (0.698; 0.744)	87 (82; 93)	0.36 (0.33; 0.39)	0.94 (0.93; 0.95)	0.88 (0.86; 0.90)
	stick	285 (244; 325)	0.697 (0.673; 0.721)	94 (88; 100)	0.39 (0.36; 0.43)	0.93 (0.92; 0.94)	0.86 (0.85; 0.88)
PF	**belt**	569 (500; 639)	0.573 (0.541; 0.605)	179 (168; 191)	0.63 (0.56; 0.69)	0.85 (0.82; 0.87)	0.72 (0.67; 0.76)
	stick	607 (541; 672)	0.530 (0.502; 0.559)	174 (164; 186)	0.60 (0.55; 0.67)	0.86 (0.83; 0.88)	0.74 (0.69; 0.77)
MP	**belt**	364 (299; 430)	0.596 (0.572; 0.620)	196 (185; 209)	0.45 (0.41; 0.50)	0.91 (0.89; 0.93)	0.83 (0.79; 0.86)
	stick	434 (364; 504)	0.531 (0.507; 0.555)	215 (202; 229)	0.50 (0.46; 0.56)	0.89 (0.87; 0.91)	0.79 (0.76; 0.83)
PP	**belt**	1248 (1113; 1382)	0.471 (0.445; 0.498)	443 (417; 473)	0.64 (0.57; 0.71)	0.84 (0.82; 0.87)	0.71 (0.67; 0.76)
	stick	1244 (1064; 1424)	0.470 (0.434; 0.505)	538 (507; 574)	0.86 (0.77; 0.97)	0.76 (0.72; 0.79)	0.58 (0.52; 0.62)
MV	**belt**	0.57 (0.48; 0.66)	0.507 (0.459; 0.556)	0.11 (0.10; 0.11)	1.07 (0.94; 1.22)	0.68 (0.63; 0.73)	0.46 (0.40; 0.53)
	stick	0.60 (0.54; 0.67)	0.456 (0.424; 0.487)	0.09 (0.08; 0.10)	0.78 (0.70; 0.88)	0.79 (0.75; 0.82)	0.62 (0.56; 0.67)
PV	**belt**	0.85 (0.73; 0.97)	0.553 (0.514; 0.591)	0.14 (0.13; 0.15)	0.79 (0.71; 0.89)	0.78 (0.75; 0.82)	0.61 (0.56; 0.67)
	stick	1.05 (0.91; 1.19)	0.473 (0.430; 0.515)	0.16 (0.16; 0.18)	1.02 (0.90; 1.17)	0.70 (0.65; 0.74)	0.49 (0.42; 0.55)
jump height (force impulse)	**belt**	-0.3 (-1.4; 0.8)	0.787 (0.759; 0.815)	2.2 (2.1; 2.4)	0.4 (0.37; 0.44)	0.93 (0.91; 0.94)	0.86 (0.83; 0.88)
	stick	0.6 (-0.5; 1.8)	0.738 (0.710; 0.766)	2.4 (2.2; 2.5)	0.43 (0.39; 0.48)	0.92 (0.90; 0.93)	0.85 (0.81; 0.86)
jump height (flight time)	**belt**	-1.2 (-2.5; 0.0)	0.845 (0.813; 0.877)	2.5 (2.4; 2.7)	0.43 (0.39; 0.47)	0.92 (0.90; 0.93)	0.85 (0.81; 0.86)
	stick	-0.6 (-1.9; 0.6)	0.801 (0.771; 0.831)	2.5 (2.4; 2.7)	0.43 (0.39; 0.47)	0.92 (0.90; 0.93)	0.85 (0.81; 0.86)
RFD	**belt**	0.6 (-13.4; 14.6)	1.362 (1.136; 1.589)	55.2 (52.0; 58.9)	1.88 (1.57; 2.3)	0.47 (0.40; 0.54)	0.22 (0.16; 0.29)
	stick	15 (-0.5; 30.4)	0.961 (0.744; 1.178)	58.2 (54.8; 62.1)	2.55 (2.04; 3.35)	0.37 (0.29; 0.44)	0.14 (0.08; 0.19)
RFD *	**belt**	1.146 (0.705; 1.862)[a]	1.015 (0.894; 1.136)[b]	1.62 (1.57; 1.67)[c]	1.35 (1.17; 1.57)	0.60 (0.54; 0.65)	0.36 (0.29; 0.42)
	stick	1.329 (0.779; 2.269)[a]	0.942 (0.814; 1.071)[b]	1.65 (1.60; 1.71)[c]	1.54 (1.32; 1.83)	0.54 (0.48; 0.60)	0.29 (0.23; 0.36)

* log-transformed data and fitted by calibration equation Y = aX^b, where Y denotes the value of force plate, and X is the value from LPT; [a] coefficient a in calibration equation; [b] coefficient b in calibration equation; [c] typical error of estimate (TEE) as a ×/÷ factor; r – Pearson correlation; r^2 – coefficient of determination. MF = mean force, PF = peak force, MP = mean power, PP = peak power, MV = mean velocity, PV = peak velocity, RFD = rate of force development.

TABLE 3. The reliability of measures on the force plate and two linear position transducer placement.

Type of measurement		Mean force	Peak force	Mean power	Peak power	Mean velocity	Peak velocity	Jump height	Rate of force development
Belt	ICC (2,1)	0.888	0.765	0.841	0.790	0.433	0.590	0.853	0.601
	ICC (2,k)	0.966	0.911	0.945	0.926	0.705	0.810	0.956	0.820
	CV	5.6%	7.5%	8.2%	10.6%	5.4%	4.5%	5.3%	16.3%
Stick	ICC (2,1)	0.884	0.812	0.850	0.678	0.657	0.606	0.839	0.673
	ICC (2,k)	0.977	0.959	0.971	0.899	0.88	0.851	0.956	0.873
	CV	5.9%	8.2%	9.1%	12.5%	5.5%	5.2%	6,0%	13.8%
Force Plate	ICC (2,1)	0.904	0.840	0.888	0.845	0.669	0.601	0.859	0.513
	ICC (2,k)	0.977	0.961	0.976	0.972	0.897	0.923	0.962	0.902
	CV	4,0%	5.8%	6.1%	6.3%	4,0%	4.3%	5.4%	30.2%

Linear regression equations were used to calculate practical (i.e. LPT) values to criterion (i.e. force plate) values. The typical error of estimate (absolute and standardized), Pearson correlation r, coefficient of determination r^2, and values of slope and intercept were calculated with 95% confidence intervals. The coefficient of determination explains the proportion of variance explained by the regression model and serves as an indicator of systematic bias. Pearson correlation values were considered: Mean bias and typical error of estimate (TEE) were expressed as a factor in the case of RFD, where log-transformation of data was required.

A model in R software (R Foundation, Vienna, Austria) was developed to analyse the distribution of variance to compare the force plate and LPT reliability. The total variance was divided into the following categories with the following degrees of freedom (in brackets): persons, repetition (5), set (2), session (2), all possible interactions between the categories and residual. Two-way random, single measures, absolute agreement intra-class correlation ICC (2, 1), and two-way random, average measures, absolute agreement ICC (2, k) were used to assess relative reliability [30].

ICC (2, 1) was calculated as the ratio of the variance of participants σ_P to total variance σ_{TOT}, whereas ICC (2, k) was calculated by the formula:

$$ICC(2,k) = \frac{\sigma_P}{\sigma_P + \sum \frac{\sigma_i}{dof_i}}$$

where σ_i denotes the variance of each category and dof_i is the degrees of freedom of each category of variance and all of their possible interactions. ICC was considered to be excellent (ICC = 0.9–1.0; very high 0.7–0.9 and high 0.5–0.7). The coefficient of variation (CV) for each participant was calculated for each observed variable. The mean CV is reported for each parameter as a percentage, and the threshold of acceptability value was < 10% [29].

RESULTS

The results of validity are presented in Tables 1 and 2. The mean and standard deviation of all methods, average bias, and standardized bias with confidence intervals are presented in Table 1. The RFD results are presented as absolute and log-transformed, which led to better agreement between LPT and force plate measurements.

Values of coefficients for recalculation equations, the typical error of estimate (absolute and standardized), Pearson correlation, and coefficient of determination are all presented in Table 2 with 95% confidence intervals.

The results of the reliability of all devices are presented in Table 3. Most parameters showed acceptable reliability except the mean and peak velocity on the belt and both placements in the rate of force development.

DISCUSSION

Both LPT attachments sites provided reliable results, but although the LPT was reliable, the force plate resulted in more reliable data. Furthermore, the LPT tended to overestimate all the observed values compared to force plate data. Specifically, the LPT exhibited a positive systematic bias when measuring concentric force (average and peak), jump height, and average concentric power. For velocity measures, the variance was similarly distributed between systematic and random bias, while the variance of measuring peak power was due to systematic bias rather than random (71% in belt placement, 58% in stick placement). However, in the case of RFD, the bias was mostly random (78% belt, 86% stick). The magnitude of overestimation varied from moderate (force), moderate to large (jump height, power), to very large (velocity). A comparison of TEE and bias (both absolute and standardized, in Tables 1 and 2) showed that using recalculation equations led to a much more accurate assessment of the value of the observed variable.

Both LPT attachment sites provided reliable results, especially when using the average value of measurement ICC (2, k), because using the average value provides better reliability. Excellent reliability was achieved in MF, PF, MP, PP, and jump height, and very high reliability was achieved in MV and PV. However, the CV of PP was over 10%. This corresponds to the nature of PP and MP measurements, when even the gold standard measuring device showed a greater CV for power measures compared to force or velocity parameters. RFD had very high relative reliability, but due to CVs over 10%, it should not be treated as reliable, even though the LPT CV was much lower than the CV of the force plate. If we focus on the absolute agreement of single measures, relative reliability looks similar to the force plate in the case of MF, PF, MP, PV, and jump height.

The findings of validity in mean force and peak force correspond to previous studies [22, 31, 32] where mean force assessment had higher agreement than peak force. Both variables were measured accurately by the LPT in the current study with little overestimation and excellent agreement, similar to previous findings [24, 33]. The LPT attached to the belt showed better agreement in results of force than when the LPT was attached to the stick, which is similar to the findings of accelerometer systems that were placed at two different sites during CMJs [34]. As the reliability of both attachments provides similar results to the force plate, the LPT may be considered both valid and reliable for measuring MF and PF.

The validity and reliability of velocity remain questionable. Both MV and PV exhibited a large amount of systematic (standardized bias and standardized TEE in Tables 1 and 2) and random bias (r^2 = 0.46–0.62). Generally, the findings of earlier studies are inconsistent when determining whether an LPT is a valid tool for measuring peak or mean velocity. Similar to the results of other studies [23, 25, 32, 33, 35, 36], our findings confirmed the tendency that as movement velocity increased, the level of agreement between the force plate and LPT decreased. Additionally, the reliability of MV measured on the belt attachment is at the lower border of the ‘very high’ range (ICC = 0.705), the other ICCs of MV and PV exceed 0.80, while the CV remained clearly within acceptable limits (4.5%–5.5%). Surprisingly, the stick attachment was more reliable for assessing PV and MV than the belt attachment. This is surprising because the stick has the opportunity to pivot about the shoulders in the frontal plane, meaning that the end of the bar (where the attachment site is) may move at a faster or slower rate of speed compared to the relatively stable (lack of) movement that can occur at the belt attachment site. Nevertheless, the experienced jumpers who were the subjects of the present study were seemingly able to maintain a stable stick position on their back, resulting in reliable data. Having said that, it is possible that less experienced jumpers may not produce the same reliable pattern.

Furthermore, the force plate provided more reliable results than both LPT attachments. This particularly disagrees with a previous study [33], which reported significantly higher ICC for MV (0.84 compared to 0.705 in our study). Considering the inter-individual differences that may occur during jumping, the lower ICC values of single measurements may derive from inconsistency in the performance of each participant. One source of bias may be that the fixed LPT attachment site on the waist does not correspond to the centre of mass, as an imaginary point, which may move relative to the attachment. Therefore, this might be a source of the bias, especially if the LPT is attached to the stick. However, reliability favoured stick attachment. An additional explanation of bias and consistency in performance is that they are due to the derivation of displacement (LPT) compared to the integration of force (force plate); both these operations are sources of error.

Peak and mean power as a product of force and velocity showed lower agreement than force and higher agreement than velocity. Correlation and bias values are similar to those of other LPT validation studies [16, 32, 33]. However, stick attachment leads to a significantly higher bias of PV than attachment to the belt, naturally, as a consequence of PV bias. This agrees with conclusions of loaded squat or squat jump studies [31, 32, 36], where low-force, high-speed exercise proved lower agreement than high-force, low-speed exercise. The reliability of PP and MP measurement remains questionable: while ICC of average measures shows excellent agreement, PP reliability of single measures dropped below 0.7, and CVs in PP (both attachments) were higher than 10%.

Jump height provided by the LPT systematically overestimates the height obtained by both methods (force impulse and flight time) from the force plate. Both LPT placements showed excellent agreement (r = 0.92–0.93) but also high systematic bias (7.2–9.8 cm). These values confirmed the results of previous research [32, 35]. The attachment to the stick showed 1.3–1.4 cm higher bias than attachment to the belt, which may be caused by a complete extension of the trunk during the terminal take-off and flight phase of the jump. Similarly, the reliability of both attachments exhibits almost identical values to those obtained by the force plate and only confirms the recent findings [25, 35] demonstrating that the LPT is a valid and reliable device to measure jump height.

The most complicated and less accurate estimation was observed in RFD. Even though relative reliability shows very high values, CV was too far over the threshold (16.3% belt; 13.8% stick). The problem of validation was the lowest reliability results obtained by the force plate (CV 30.2%, single measures ICC = 0.513). Therefore, the bias was mostly random, even when the data were log-transformed. The belt provides better agreement than the stick, but it is still not accurate. These methods of RFD estimation do not match. The reason for the random nature of bias might arise from the two-peak force curve during the take-off phase in some participants and calculation algorithms, which indicates an eccentric/concentric switch and peak force instant. These “two-peak” participants do not necessarily perform their peak value consistently in either the first or the second peak in each jump, which subsequently strongly influences the value of RFD. Hansen et al. [24] also confirmed the very poor agreement of RFD estimation by the LPT and force plate in loaded CMJ.

The LPT may serve as a suitable device in the measurement of explosive strength parameters in unloaded jumps. It provides excellent reliable data for peak or mean force and jump height and very highly reliable data of peak and mean power or velocity. If coaches, athletes, or scientists need to compare values of parameters obtained from various devices, we strongly recommend using linear regression equations to recalculate results obtained from the LPT. This recalculation significantly decreases the range of systematic bias (bias vs TEE and their confidence intervals). The bias in mean/peak force/power and jump height is mostly systematic, while in mean/peak velocity it is proportionally similar. The most random bias was observed in the assessment of the rate of force development.

CONCLUSIONS

The assessment of explosive strength parameters is most accurate and reliable when using a force plate. Our study confirmed that a linear position transducer may efficiently substitute the force plate in obtaining valid and reliable results of force, power, and jump height. A little less accuracy is provided for velocity assessment. As the data from the LPT are at least very highly reliable, they may subsequently be valid. The validity of the LPT shows mostly systematic bias, which may be simply reduced by using recalculation equations.

Attachment to the stick placed on the athlete's shoulders produced very similar results to attachment placed on a belt, which is traditionally recommended for unloaded jumps except for the mean velocity. Both attachments can be recommended as long as measurers use them consistently.

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Conflict of interest declaration

The authors declared no conflict of interest.

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