Validity and Reliability of Methods to Determine Barbell Displacement in Heavy Back Squats: Implications for Velocity-Based Training

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ABSTRACT

Appleby, BB, Banyard, H, Cormack, SJ, and Newton, RU. Validity and reliability of methods to determine barbell displacement during heavy back squats. J Strength Cond Res 34(11): 3118–3123, 2020—The purpose of this study was to investigate the validity and reliability of methods for determining barbell displacement during heavy back squats. Twelve well-trained rugby union players (mean ± SD 1 repetition maximum [1RM] 90% squat = 196.3 ± 29.2 kg) completed 2 sets of 2 repetitions at 70, 80, and 90% of 1RM squats. Barbell displacement was derived from 3 methods across 4 load categories (120–129, 140–149, 160–169, and 180–189 kg) including: (a) linear position transducer (LPT) attached 65 cm left of barbell center, (b) 3D motion analysis tracking of markers attached to either end of a barbell, and (c) cervical marker (C7) (criterion measurement). Validity was calculated using the typical error of the estimate as a coefficient of variation (CV%) ±90% confidence interval (CI), mean bias as a percentage, and the Pearson product moment correlation (r). Intraday reliability was calculated using the typical error expressed as a percentage of CV% ±90% (CI). Mean displacement for C7, LPT, and the barbell ends was 520, 529, and 550–564 mm, respectively. Validity of the LPT compared with the criterion was acceptable (CV% = 2.1–3.0; bias = 0.9–1.5%; r = 0.96–0.98), whereas that of the barbell ends was less (CV% = 2.7–7.5; bias = 4.9–11.2%; r = 0.71–0.97). The CV% reliability of the C7 marker across the load categories was 6.6%, the LPT 6.6%, and the barbell ends between 5.9 and 7.2%. Despite reliable measures, overestimation of displacement occurs as the tracking location moves to the barbell ends in weighted back squats. The LPT demonstrated high validity to the criterion and high trial-to-trial reliability.

KEY WORDS barbell velocity, linear position transducer, 3D motion analysis

INTRODUCTION

Barbell displacement is the measurement of change in barbell position during a resistance exercise (13). Accurate quantification of barbell displacement in exercises such as the squat is critical for the measurement of barbell velocity (1,13,19). Methods to assess barbell displacement often involve indirect methods (optical motion sensors, such as V-scope), direct methods (attachment of an accelerometer or tether, such as a linear position transducer [LPT]), or a configuration of force plate and LPT (13,21). Many researchers have investigated the validity and reliability of LPTs to extrapolate variables derived from displacement, such as velocity, force, and power (8,9,11). However, it has been well documented that although mathematically sound in principle, there are limitations associated with this method for the accurate assessment of barbell displacement, such as potential for uneven horizontal or vertical displacement and the barbell leaving the body, which can be problematic at lighter loads (6,12,13,16,23,24). In addition, error in calculating displacement can be multiplied through subsequent calculations determining acceleration and power (16).

In the free-weight barbell movement, researchers identified subtle horizontal vectors in barbell displacement as a source of error using single LPTs (6,7). Subsequent researchers have incorporated the practice of left and right paired LPTs to extract vertical displacement as a representation of the center of the...
barbell (2,3,25). Of additional consideration in tracking vertical displacement in free-weight barbell squats may be the flexible design of weightlifting barbells (4). Significant differences of 4 cm have been reported in the execution of the clean pull between displacement measured from the barbell end or barbell center (5). Furthermore, the absolute loads used in previous research may not have been sufficient for adequate distortion of the barbell during ballistic heavy squats, which are used in highly strength-trained athletes (2,3,25). This is yet to be established in back squats where the presence of the eccentric phase may increase displacement due to the elasticity of the barbell.

Therefore, the purpose of this study was to determine the validity of 2 methods of barbell displacement compared with a criterion measure and calculate the reliability of displacement in heavily loaded back squats.

**METHODS**

**Experimental Approach to the Problem**

Twelve well-trained participants attended 2 testing sessions. In session 1, a 1 repetition maximum (1RM) 90° back squat was established. Participants attended a second testing session where they completed 2 sets of 2 repetitions of 70, 80, and 90% 1RM squat. The validity and reliability of barbell displacement was assessed using 3D motion analysis and an LPT.

**Subjects**

Twelve academy and professional-level rugby union players with a mean age, body mass, and 1RM squat of mean ± SD: 24.5 ± 5.2, age range: 19-30 years; 102.7 ± 10.4 kg; 184.8 ± 5.1 cm; 196.3 ± 29.2 kg, respectively participated in this study. All participants were notified of the potential risks involved and provided written informed consent. This study was approved by the Edith Cowan University’s Human Research Ethics Committee. All participants acknowledged to be free of injury or previous injury history, which may have inhibited performance.

**Procedures**

**One Repetition Maximum Testing.** The 1RM protocol has been used for assessment of maximal strength (20), and the coefficient of variation (CV) for squat testing has been reported to be 3.5% (22). The protocol involved participants completing a series of warm-up sets (4 repetitions at 50% of estimated 1RM, 3 repetitions at 70%, 2 repetitions at 80%, and 1 repetition at 90%), each separated by 3 minutes recovery. After the warm-up, maximal attempts separated by a minimum of 5-minute recovery were performed until a 1RM was obtained. Verbal encouragement was provided throughout the testing. The 90° knee flexion depth was monitored by each participant squatting with a 20-kg Olympic barbell (Australian Barbell Company, Victoria, Australia) and Olympic weight plates (Eleiko, Halmstad, Sweden) to an elastic band placed on both sides of a power rack (York Fitness, Rocklea, Queensland, Australia) at their individually determined depth. An accredited S&C coach and at least one assistant observed each test for spotting, technique, and depth monitoring. The repetition was deemed a fail if the participant could not achieve the required depth, or could not return to the upright position.

**Table 1.** Validity of the criterion measure (seventh cervical vertebrae marker) in the back squat barbell to the RHS, LHS, and LPT displacement by absolute bar load.*†

| Measure | kg | n   | Typical error as a CV% (CI) | Pearson correlation (CI) | Overall mean bias as a % (CI) |
|---------|----|-----|-----------------------------|--------------------------|-------------------------------|
| LPT     |    |     |                             |                          |                               |
| 120–129 | 18 | 2.1 | (1.6–2.9)                   | 0.98 (0.96–0.99)         | 0.9 (0.0–1.8)                  |
| 140–149 | 32 | 2.5 | (2.0–3.2)                   | 0.98 (0.96–0.99)         | 1.4 (0.7–2.2)                  |
| 160–169 | 28 | 3.0 | (2.4–3.9)                   | 0.96 (0.92–0.98)         | 1.4 (0.4–2.4)                  |
| 180–189 | 20 | 2.4 | (1.9–3.3)                   | 0.97 (0.93–0.98)         | 1.5 (0.6–2.4)                  |
| All loads | 98 | 2.5 | (2.2–2.8)                   | 0.97 (0.96–0.98)         | 1.3 (0.9–1.8)                  |
| RHS     |    |     |                             |                          |                               |
| 120–129 | 20 | 7.5 | (5.9–10.6)                  | 0.71 (0.45–0.86)         | 7.3 (4.2–10.4)                 |
| 140–149 | 34 | 4.0 | (3.3–5.1)                   | 0.94 (0.89–0.96)         | 7.7 (6.5–9.0)                  |
| 160–169 | 30 | 3.3 | (2.7–4.2)                   | 0.95 (0.90–0.97)         | 9.7 (8.5–10.9)                 |
| 180–189 | 20 | 3.9 | (3.1–5.4)                   | 0.91 (0.81–0.96)         | 11.2 (9.5–12.9)                |
| All loads | 104 | 4.7 | (4.2–5.4)                   | 0.89 (0.85–0.92)         | 8.9 (8.0–9.7)                  |
| LHS     |    |     |                             |                          |                               |
| 120–129 | 20 | 2.7 | (2.1–3.7)                   | 0.97 (0.93–0.98)         | 5.0 (3.7–6.3)                  |
| 140–149 | 34 | 3.4 | (2.8–4.3)                   | 0.95 (0.92–0.97)         | 6.6 (5.5–7.6)                  |
| 160–169 | 30 | 3.4 | (2.8–4.4)                   | 0.94 (0.89–0.97)         | 4.9 (3.8–6.0)                  |
| 180–189 | 20 | 3.1 | (2.5–4.4)                   | 0.94 (0.87–0.97)         | 7.3 (6.0–8.5)                  |
| All loads | 104 | 3.3 | (2.9–3.7)                   | 0.95 (0.93–0.96)         | 5.9 (5.3–6.5)                  |

* n = number of trials included in analysis; CV = coefficient of variation; CI = 90% confidence interval; Overall mean bias as a % = difference between criterion and predicted measures; LPT = linear position transducer, attached to the furthest LHS of the grip section of the barbell; RHS = right-hand side of the barbell; LHS = left-hand side of the barbell.

†Data presented as mean ± 90% CI for all variables.
Squat Displacement Assessment. An average of 6 days separated 1RM testing and testing session 2. Session 2 involved a biomechanical assessment of the back squat. After the standardized general body warm-up consisting of 10 minutes of moderate-intensity stationary bike riding, followed by 10 minutes of self-directed stretching and mobility exercises, participants performed 2 sets of 4 repetitions of squats at body weight. Participants than performed warm-up sets at 50 and 60% 1RM for 6 and 4 reps, respectively. The assessment sets involved the participant performing 2 sets of 2 repetitions at 70, 80, and 90% 1RM. As highly trained participants, they were requested to perform the eccentric phase at self-selected pace (2,3) and were required to perform the concentric phase as “explosively” as possible. Technique was monitored according to the same protocols as 1RM testing.

Three-Dimensional Motion Analysis. During all squat assessments, a 10-camera digital optical motion analysis system (Vicon MX; Vicon, Oxford, United Kingdom) was used to capture whole-body 3-dimensional movement patterns at 250 Hz. A previously validated, whole-body model was used to capture and analyze movement patterns using Nexus software (Nexus 1.0 capture and Nexus 2.0 analysis) (10). The model uses a defined, 37 retroreflective marker set and series of participant measurements. Two-dimensional marker trajectories were reconstructed to 3-dimensional using a custom pipeline and filtered using a fifth-order Woltring routine (spline interpolation filter). An area of approximately 25 square meters to a height of approximately 3 meters was calibrated using a wand calibration. All data were analyzed using customized processes in Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA, USA).

Criterion Marker. Incorporated in the full-body marker set, a retroreflective marker was placed on the skin at the landmark of the seventh cervical vertebrae. This marker was selected as an appropriate criterion marker due to its close proximity to the barbell center during the back squat.

Barbell Marker. Three locations were used in the assessment of barbell travel: motion analysis markers placed on both ends of the barbell (left-hand side [LHS] and right-hand side [RHS]) and the LPT (see below for attachment position details). Barbell displacement was calculated using motion analysis (LHS, RHS, and C7 [criterion variable]: the difference between the minimum and maximum z-axis coordinates for each repetition was classified as the displacement) and the measurement of displacement from the LPT.

### Table 2. Reliability of the criterion measure (seventh cervical vertebrae marker), the RHS, LHS, and LPT displacement in back squat barbell displacement by absolute bar load.*†

| Measure | Barbell load (kg) | n | Mean range (mm ± SD) | CV% (±90 CI) | Intraclass correlation (±90 CI) |
|---------|------------------|---|----------------------|-------------|-------------------------------|
| LPT | 120–129 | 5 | 529 ± 57 | 9.0 (6.4–15.9) | 0.60 (0.12–0.91) |
| | 140–149 | 9 | 541 ± 60 | 4.8 (3.8–6.9) | 0.86 (0.69–0.95) |
| | 160–169 | 8 | 524 ± 63 | 7.8 (6.0–11.4) | 0.68 (0.37–0.89) |
| | 180–189 | 5 | 512 ± 49 | 7.3 (5.4–12.6) | 0.60 (0.16–0.91) |
| All loads | 27 | 528 ± 56 | 6.6 (5.5–8.4) | 0.67 (0.46–0.82) |
| RHS | 120–129 | 5 | 559 ± 36 | 8.1 (5.6–15.0) | 0.84 (0.16–0.95) |
| | 140–149 | 9 | 570 ± 54 | 5.0 (4.0–7.5) | 0.84 (0.65–0.95) |
| | 160–169 | 8 | 560 ± 52 | 7.6 (5.8–11.1) | 0.58 (0.24–0.85) |
| | 180–189 | 5 | 558 ± 42 | 7.1 (5.2–12.2) | 0.63 (0.20–0.92) |
| All loads | 27 | 564 ± 55 | 5.9 (4.8–7.8) | 0.67 (0.44–0.84) |
| LHS | 120–129 | 5 | 549 ± 45 | 10.1 (7.0–18.8) | 0.72 (0.27–0.96) |
| | 140–149 | 9 | 565 ± 55 | 5.6 (4.4–8.4) | 0.80 (0.57–0.93) |
| | 160–169 | 8 | 536 ± 50 | 6.2 (4.8–9.0) | 0.90 (0.78–0.96) |
| | 180–189 | 5 | 540 ± 36 | 7.3 (5.4–12.6) | 0.80 (0.62–0.92) |
| All loads | 27 | 550 ± 56 | 7.2 (5.9–9.2) | 0.55 (0.32–0.75) |
| C7 | 120–129 | 5 | 523 ± 38 | 9.3 (6.9–16.2) | 0.34 (–0.08–0.82) |
| | 140–149 | 9 | 530 ± 52 | 4.4 (3.5–6.6) | 0.88 (0.72–0.96) |
| | 160–169 | 8 | 520 ± 49 | 6.2 (4.8–9.0) | 0.72 (0.42–0.91) |
| | 180–189 | 5 | 504 ± 40 | 7.3 (5.4–12.5) | 0.59 (0.15–0.91) |
| All loads | 27 | 520 ± 52 | 6.6 (5.3–9.2) | 0.62 (0.33–0.82) |

* n = number of trials included in analysis; mean range in mm ± SD; CV = coefficient of variation; CI = 90% confidence interval; LPT = GymAware linear position transducer, attached to the furthest LHS of the grip section of the barbell; RHS = right-hand side of the barbell; LHS = left-hand side of the barbell; C7 = seventh cervical vertebrae marker.
† Data presented as mean ± SD or mean ± 90% CI for variables as indicated.
**Linear Position Transducer.** A GymAware LPT (GymAware PowerTool Version 5; Kinetic, Canberra; interfaced through Bluetooth to an Apple iOS device, Apple iPad Mini v1) was attached to the furthest position of the grip section of the LHS of the barbell for all trials (approximately 65 cm from the center of the bar). The GymAware device transmits data through Bluetooth to a tablet (iPad, Apple, Inc., Cupertino, CA, USA). Data are sampled at 20 ms time points, and the setup and use has been previously detailed (2).

**Statistical Analyses**

Analysis of validity was performed using a customized Excel spreadsheet (14). The typical error of the estimate as a coefficient of variation ±90% confidence interval (CV% ± 90% CI), mean bias as a percentage, and the Pearson product-moment correlation (r) between the criterion (C7) and practical variables (RHS, LHS, and LPT) was calculated. Intraday reliability was calculated using the intraclass correlation coefficient (ICC) and the typical error expressed as a percentage (CV%) ±90% CI using a customized Excel spreadsheet (15).

**RESULTS**

The validity of each marker relative to the C7 marker is presented in Table 1. The bias between the criterion (C7) and predicted measure increased with laterality of marker position and magnitude of bar load (LPT bias = 0.9–1.5%; r = 0.96–0.98; barbell ends' bias = 4.9–11.2%; r = 0.71–0.97). Moderate reliability was obtained for most measures of barbell displacement (all loads: LPT: CV% = 6.6%, ICC = 0.67; barbell ends: CV% = 5.9–7.2%, ICC = 0.55–0.67; C7: CV% = 6.6%, ICC = 0.62) (Table 2). The barbell mean displacement increased as the point of measure moved to the extremity (all loads: C7 = 520 mm; LPT = 529 mm; LHS = 550 mm; RHS = 564 mm).

**DISCUSSION**

This study sought to determine the validity of barbell displacement in heavy back squats measured at various points on the bar using motion analysis and LPT, compared with the C7 criterion marker. In addition, the trial-to-trial reliability of each method in determining displacement was also assessed. The primary findings of this work are: (a) the LPT positioned on the end of the grip (65 cm from the barbell center) was the most valid of the methods compared with the C7 marker, (b) the extent of barbell load and the position of tracking method can influence the validity of barbell travel estimates; however, (c) measures of barbell displacement across a range of loads in the barbell back squat using LPT or motion analysis of C7 and barbell end markers are reliable. Given the fact that velocity is calculated from displacement, overestimations of barbell displacement (all loads: C7 = 520 mm or LPT = 529 vs. LHS = 550 mm or RHS = 564 mm; Table 2) have implications for the interpretation of barbell velocity and subsequent calculations of acceleration, force, and power.

The accurate measurement of barbell displacement is central to the calculation of power in squats and to the growing field of velocity-based training (VBT) (12,18,19). In the current study, assessment of the C7 criterion measure through the use of 3D motion analysis permits determination of vertical displacement from the z-axis coordinates only, removing extraneous horizontal movement from displacement calculations. The current findings suggest that bias of barbell displacement measurement increased as the site of measurement moved from the barbell center as demonstrated by the differences in bias between the LPT (0.9–1.5% mean bias) and barbell ends (LHS = 4.9–7.3%; RHS = 7.3–11.2%) (Table 1). The differences in mean bias would indicate decreasing validity in the accuracy of barbell velocity estimations because barbell displacement (used in the calculation of barbell velocity) is affected by the combination of the location of bar measurement and the magnitude of external mass. This may be explained by the inherent deformation qualities of a weightlifting barbell that permit the barbell to bend under load, creating a discrepancy in vertical height between the barbell center and barbell ends, with the difference being a positive relationship with external load (4). The lower mean bias for LPT (<1.5%) across each load condition indicates that the LPT position is acceptable, even when the pliant nature of the barbell is considered (Table 1). With the extremities of the barbell loaded, creating a central flexion point in the barbell, markers other than the center of the barbell may travel greater absolute ranges (5). This is demonstrated by the greater bias between the C7 criterion and RHS and LHS variables with increasing barbell load (Table 1). This finding supports previous work reporting a difference between the center and barbell ends (5). The findings of this investigation may be particularly important, given the growing prevalence of VBT and the fundamental requirement for the accurate assessment of barbell displacement. As load increases, displacement calculated in a lateral, as opposed to central, location is more likely to overestimate the displacement travelled (Table 1). At heavy loads, the flexibility in the barbell may cause the extremities to achieve a lower depth than the center of the barbell, whereas the elastic recoil of the barbell may facilitate a higher maximum value in rapid extension (4). The influence of barbell flexibility can be observed by the increasing displacement values as the measurement point moved away from the center of the barbell. Accurate displacement data are a critical base measure for the determination of velocity and subsequent differentiation to determine acceleration (17).

To overcome any asymmetrical bar path performance in a single-side measurement, an overhead mounted, paired LPT system attached to each end of the grip section of the barbell has been used (2,3,25). The displacement at the center of the barbell is inferred by averaging the calculated displacement of the barbell ends. Investigating the validity of measures of barbell velocity, Banyard et al. (2), using the 4-LPT system, concluded that the LPT was accurate.
Although our study explored displacement, the LPT was found to be valid, confirming the conclusions of Banyard et al. (2). Given the low bias across the load spectrum in this experiment (0.9–1.5%) between the LPT and C7 marker in the current study (Table 1), it suggests similarity between the 2 positions and that the LPT may be a valid representation of central barbell trajectory.

Reliability is a fundamental requirement of any testing apparatus reporting measures of human performance to confidently distinguish between “noise” in a test and meaningful change. In the current study, both the extremities of the barbell and the LPT were deemed reliable (Table 2). The reliability of peak velocity, derived from displacement using a LPT, has been previously established in 20-kg barbell jump squats (CV% = 1.3–2.6) (16). The heavier barbell mass used in the current study may have introduced more variation in bar displacement resulting in larger CV%. Historically, investigations in LPT reliability have typically concerned unweighted or lightly weighted jump squats, with few explicitly observing the influence of absolute barbell load on barbell qualities. An important feature of the current study is the investigation of the magnitude of external mass used and the effect of load on the elastic nature of the barbell (5). Barbells are manufactured with a degree of flexibility for safety and enhanced lifting performance (4) and the influence of load and barbell composition on measures of displacement in back squats has escaped investigation. Therefore, using a single-end measurement, or averaging both ends of the barbell, may misrepresent the center of the barbell, given the elastic deformation of a heavy barbell (5).

It must be acknowledged that this investigation contains a number of limitations. First, the number of participants is low and future studies wishing to replicate this investigation should use a greater participant number and participants of a wider range of strength capacity. In addition, a higher load range (more than 180 kg) should also be assessed to determine how increasing loads alter barbell path characteristics.

In conclusion, the LPT proved valid in tracking vertical barbell displacement. Despite being reliable, using the ends of the barbell for tracking of vertical barbell trajectory may overestimate barbell displacement at higher loads due to the flexible nature of quality weightlifting bars. As demonstrated by the validity and reliability of the LPT, it is important to attach LPTs as central as possible, particularly given the influence of barbell mass on barbell deformation. Coaches using VBT to test and motivate athletes should ensure consistent LPT attachment position, as central as possible.

Practical Applications

Despite acceptable reliability of all measurements, the LPT proved most valid compared with the criterion C7 marker when attached to the center with excessive bias measured at the barbell ends. This is likely to be an issue as the barbell load increases, leading to overestimation of velocity measures. Therefore, coaches using LPTs for VBT should seek methods that permit centralizing the location of attachment as much as possible (e.g., overhead mounted) to maximize the validity of displacement assessment, particularly in heavy back squats. Furthermore, future research in heavy, free barbell trajectory should avoid using the barbell ends and attempt to centralize measures of barbell displacement.

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