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# Validity and reliability of methods to determine barbell displacement in heavy back squats: Implications for velocity-based training

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## ABSTRACT

To investigate the validity and reliability of methods for determining barbell displacement during heavy back squats. Twelve well-trained rugby union players (mean ±SD one repetition maximum 90° squat = 196.3 ± 29.2kg) completed two sets of two repetitions at 70%, 80% and 90% of one repetition maximum squats. Barbell displacement was derived from three methods across four load categories (120-129kg, 140-149kg, 160-169kg and 180-189kg) including: a [1] Linear Position Transducer (LPT) attached 65cm left of barbell centre, [2] 3D motion analysis tracking of markers attached to either end of a barbell, and a [3] 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 intraclass correlation coefficient (ICC) and the typical error expressed as a percentage of CV% ±90% (CI). Mean displacement for C7, LPT and the barbell ends was 520mm, 529mm and 550-564mm, respectively. Validity of the LPT compared to the criterion was acceptable (CV% = 2.1-3.0; bias = 0.9-1.5%; r= 0.96-0.98) whilst the barbell ends were 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 5.9-7.2%. 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.

**Keywords:** barbell velocity, linear position transducer, 3D motion analysis, strength training.

## INTRODUCTION

Barbell displacement is the measurement of change in barbell position during a resistance exercise (259). Accurate quantification of barbell displacement in exercises such as the squat is critical for the measurement of barbell velocity (17, 259, 366). 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 (259, 470). Many researchers have investigated the validity and reliability of LPTs to extrapolate variables derived from displacement, such as velocity, force and power (138, 143, 172). 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 (126, 176, 259, 290, 494, 540). Additionally, error in calculating displacement can be multiplied through subsequent calculations determining acceleration and power (290).

In the free-weight barbell movement, researchers identified subtle horizontal vectors in barbell displacement as a source of error using single LPTs (126, 128). Subsequent researchers have incorporated the practice of left and right paired LPTs to extract vertical displacement as a representation of the centre of the barbell (38, 90, 548). Of additional consideration in tracking vertical displacement in free-weight barbell squats may be the flexible design of weightlifting barbells (104). Significant differences of 4cm have been reported in the execution of the clean pull between displacement measured from the barbell end or barbell centre (105). Further, the absolute loads used in previous research may not have been sufficient for adequate distortion of the barbell during ballistic heavy squats, which are utilised in highly strength trained athletes (38, 90, 548). This has 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 the present study was to determine the validity of two methods of barbell displacement compared to 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 two testing sessions. In session one, a one repetition maximum (1RM) 90° back squat was established. Participants attended a second testing session where they completed two sets of two repetitions of 70%, 80% and 90% 1RM squat. The validity and reliability of barbell displacement was assessed using 3D motion analysis and a LPT.

*Subjects***.** Twelve academy and professional level rugby union players with a mean age, mass and 1RM squat of 24.5 ± 3.2 years; 102.7 ± 10.4 kg; 184.8 ± 5.1 cm; 196.3 ± 29.2kg respectively participated in this study. All participants were notified of the potential risks involved and gave informed consent. This study was approved by the 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 (377) and the coefficient of variation (CV) for squat testing has been reported to be 3.5% (493). The protocol involved participants completing a series of warm-up sets (four repetitions at 50% of estimated 1RM, three repetitions at 70%, two repetitions at 80% and one repetition at 90%) each separated by three minutes recovery. Following the warm-up, maximal attempts separated by a minimum of five minutes recovery were performed until a 1RM was obtained. Verbal encouragement was provided throughout the testing. The 90º knee flexion depth was monitored by each participant squatting with a 20kg 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.

*Squat displacement assessment.* An average of six days separated 1RM testing and testing session two. Session two involved a biomechanical assessment of the back squat. After the standardised 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 two sets of four repetitions of squats at body weight. Participants than performed warm-up sets at 50% and 60% 1RM for six and four reps respectively. The assessment sets involved the participant performing two sets, of two repetitions at 70%, 80% and 90% 1RM. As highly trained participants, they were requested to perform the eccentric phase at self-selected pace (38, 90) 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, UK) was used to capture whole body three-dimensional movement patterns at 250Hz. A previously validated, whole-body model was used to capture and analyse movement patterns using Nexus software (Nexus 1.0 capture and Nexus 2.0 analysis) (152). The model uses a defined, 37 retro-reflective marker set and series of participant measurements. Two-dimensional marker trajectories were reconstructed to three-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 three meters was calibrated using a wand calibration. All data was analysed using customised 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 7$^{th}$ cervical vertebrae. This marker was selected as an appropriate criterion marker due to its close proximity to the barbell centre during the back squat.

*Barbell marker.* Three locations were utilised in the assessment of barbell travel: motion analysis markers placed on both ends of the barbell (left-hand side [LHS], 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.

*Linear Position Transducer.* A GymAware LPT (GymAware PowerTool Version 5, Kinetic, Canberra; interfaced via Bluetooth to an Apple iOS device, Apple iPad Mini v1) was attached to the furthest position of the grip section of the left-hand side of the barbell for all trials (approximately 65cm from the centre of the bar). The GymAware device transmits data via Bluetooth tm to a tablet (iPad, Apple Inc., California, USA). Data is sampled at 20ms time points, and the set-up and use has been previously detailed (38).

**Statistical Analyses.** Analysis of validity was performed using a customised Excel spreadsheet (283). The Typical Error of the Estimate as a coefficient of variation ± 90% confidence limits (CV% ±90% CL), 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. Intra-day reliability was calculated using the intraclass correlation of coefficient (ICC) and the typical error expressed as a percentage (CV%) ±90% CL using a customised Excel spreadsheet (286).

## RESULTS

The validity of each marker relative to the C7 marker is presented in Table 4.1. 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 4.2). The barbell mean displacement increased as the point of measure moved to the extremity (All loads: C7 = 520mm; LPT = 529mm; LHS = 550mm; RHS = 564mm).

**Table 4.1** Validity of the criterion measure (7th cervical vertebrae marker) in the back squat barbell to the right-hand side, left-hand side and linear position transducer displacement by absolute bar load.

| Measure | Kg | *n* | Typical error as a CV% (CL) | Pearson correlation (CL) | Overall mean bias as a % (CL) |
|---|---|---|---|---|---|
| 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) |

Data presented as mean (90%CL) for all variables. **LPT:** linear position transducer, attached to the furthest LHS of the grip section of the barbell; **RHS:** Right hand side of barbell; **LHS:** Left hand side of barbell. **CV%:** coefficient of variation; **CL:** 90% confidence limit; **Overall mean bias as a %:** difference between criterion and predicted measures; **n:** number of trials included in analysis.

**Table 4.2** Reliability of the criterion measure (7th cervical vertebrae marker), the right-hand side, left-hand side and linear position transducer displacement in back squat barbell displacement by absolute bar load.

| Measure | Barbell load (kg) | *n* | Mean range (mm) | CV% (CL) | ICC (CL) |
|---|---|---|---|---|---|
| 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 | 529 (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) | 0.64 (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) |

Data presented as mean (SD) or mean (90%CL) for variables as indicated. **LPT:** GymAware linear position transducer, attached to the furthest LHS of the grip section of the barbell; **RHS:** Right hand side of barbell; **LHS:** Left hand side of barbell; **C7:** 7$^{th}$ cervical vertebrae marker; **n:** number of trials included in analysis; Mean range in millimetres ± SD; **CV%:** coefficient of variation; **CL:** 90% confidence limit.

## 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 to the C7 criterion marker. Additionally, 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 (65cm from the barbell centre) was the most valid of the methods compared to 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 via LPT or motion analysis of C7 and barbell end markers are reliable. Given the velocity is calculated from displacement over-estimations of barbell displacement (All loads: C7 = 520mm or LPT = 529 v LHS = 550mm or RHS = 564mm; Table 4.2) 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) (176, 315, 366). 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 centre 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, since barbell displacement (utilized 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 which permit the barbell to bend under load, creating a discrepancy in vertical height between the barbell centre and barbell ends; the difference being a positive relationship with external load (104). 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 4.1). With the extremities of the barbell loaded, creating a central flexion point in the barbell, markers other than the centre of the barbell may travel greater absolute ranges (105). This is demonstrated by the greater bias between the C7 criterion and RHS and LHS variables with increasing barbell load (Table 4.1). This finding supports previous work reporting a difference between the centre and barbell ends (105). 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 4.1). At heavy loads, the flexibility in the barbell may cause the extremities to achieve a lower depth than the centre of the barbell, whilst the elastic recoil of the barbell may facilitate a higher maximum value in rapid extension (104). The influence of barbell flexibility can be observed by the increasing displacement values as the measurement point moved away from the centre of the barbell. Accurate displacement data is a critical base measure for the determination of velocity and subsequent differentiation to determine acceleration (294).

In order 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 (38, 90, 548). The displacement at the centre of the barbell is inferred by averaging the calculated displacement of the barbell ends. Investigating the validity of measures of barbell velocity, Banyard and colleagues (38), utilising the four-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. (38). 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 4.1), it suggests similarity between the two 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 in order 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 4.2). The reliability of peak velocity, derived from displacement utilising a LPT has been previously established in 20kg barbell jump squats (CV% = 1.3-2.6) (290). 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 (105). Barbells are manufactured with a degree of flexibility for safety and enhanced lifting performance (104) 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 centre of the barbell given the elastic deformation of a heavy barbell (105).

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 utilise a greater participant number and participants of a wider range of strength capacity. Additionally, a higher load range (more than 180kg) 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 over estimate barbell displacement at higher loads due to the flexible nature of quality weightlifting barbells. 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 deformity. 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 to the criterion C7 marker when attached to the centre 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 centralising the location of attachment as much as possible (e.g. overhead mounted) to maximise 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 centralise measures of barbell displacement.

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