Journal of Biomechanics 152 (2023) 111587



Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech



Short communication



A markerless motion capture system can reliably determine peak trunk flexion while squatting with and without a weighted vest

J.T. Andersen [a,b], A.M. McCarthy [a,b], J.A. Wills [a,b], J.T. Fuller [a,b], G.K. Lenton [c], T.L.A. Doyle [a,b,*]

[a] Biomechanics, Physical Performance, and Exercise (BioPPEx) Research Group, Macquarie University, NSW 2109, Australia
[b] Faculty of Medicine, Health and Human Sciences, Macquarie University, NSW 2109, Australia
[c] VALD, Newstead, QLD, Australia

ARTICLE INFO

Keywords:
Reliability
Computer vision
Kinematics
Movement screening
Military

ABSTRACT

Markerless motion capture has improved physical screening efficiency in sport and occupational settings; however, reliability of kinematic measurements from commercial systems must be established. Further, the impact of torso-borne equipment on these measurements is unclear. The purpose of this study was to evaluate the reliability of HumanTrak, a markerless motion capture system, for estimating peak trunk flexion in squat movements with and without a weighted vest. Eighteen participants completed body weight squats (BWSQ) and overhead squats (OHSQ) to their maximum depth (unrestricted-range) and to a plyometric box (fixed-range) while wearing no body armour (NBA) or 9 kg body armour (BA9). Peak trunk flexion was measured using HumanTrak. Testing was performed in two sessions on one day (intra-day) and one session on a separate day (inter-day) to assess reliability. HumanTrak had a standard error of measurement $< 3.74^{\circ}$ across all movements and conditions. Reliability was good to excellent (ICC = 0.82–0.96) with very large to nearly perfect Pearson correlations ($r > 0.80$) for all comparisons except unrestricted-range BWSQ with BA9 (ICC = 0.60–0.71, $r = 0.71$). HumanTrak was more reliable for intra- than inter-day, but reliability was still excellent for almost all inter-day comparisons (ICC > 0.82). HumanTrak is reliable for detecting differences in peak trunk flexion $> 8.5^{\circ}$ when body armour is not worn and $> 10.5^{\circ}$ when body armour is worn. Practitioners can assess meaningful changes in sagittal plane trunk motion when screening squat movements regardless of whether body armour is worn.

1. Introduction

Practitioners often screen large cohorts under restricted time frames. Technological advancements can expedite assessments, but measurement reliability must be established when tracking changes over time; for instance, when measuring improvements during training or rehabilitation. Without a reliable tool, practitioners may struggle to confidently monitor progress and injury risks. Markerless motion capture with computer vision algorithms shows promise to be a fast, user-friendly method for assessing movement (Colyer et al., 2018; Papic et al., 2021). Reliability of this method is similar to marker-based motion capture for hip and knee joint angles (Bonnechère et al., 2014; Schmitz et al., 2015), but studies involving the trunk are lacking (Lopes et al., 2018).

Squats are commonly used in movement screening (Cook, 2010; Kritz et al., 2009) and changes in trunk flexion can help identify injury risk (Graci et al., 2012; List et al., 2013). Greater trunk flexion, for example, typically produces higher shear forces in the lumbar spine (Potvin et al., 1991a) which increases low back injury risk (Gallagher and Marras, 2012; Potvin et al., 1991b). Markerless motion capture could be a powerful tool to reliably inform exercise prescription. Some markerless motion capture systems are reliable for estimating trunk angles in gait (Tamura et al., 2020) and reaching tasks (Clark et al., 2012); however, it is unclear whether trunk flexion in a squat can be assessed when body landmarks may be blocked from the cameras' view.

Donning body armour while performing military-type tasks presents unique challenges to physical screening. Reductions in mobility (Mitchell, 2013, 2017) necessitate screening with and without body

* Corresponding author at: Department of Health Sciences, Faculty of Medicine, Health, and Human Sciences, Macquarie University, 75 Talavera Rd, Macquarie Park, NSW 2109, Australia.
E-mail addresses: jordan.andersen@mq.edu.au (J.T. Andersen), ayden.mccarthy@hdr.mq.edu.au (A.M. McCarthy), jodie.wills@mq.edu.au (J.A. Wills), joel.fuller@mq.edu.au (J.T. Fuller), g.lenton@vald.com (G.K. Lenton), tim.doyle@mq.edu.au (T.L.A. Doyle).

https://doi.org/10.1016/j.jbiomech.2023.111587
Accepted 10 April 2023
Available online 13 April 2023
0021-9290/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

armour to determine the effects of protective vests. Changes to a person's visual characteristics when donning armour may affect determination of joint angles. The purpose of this study was to assess the intra- and inter-day reliability of a markerless motion capture system for determining peak trunk flexion angles during squat movements with and without body armour. We hypothesised that reliability would decrease when body armour was donned, but still be highly reliable for practical use.

2. Methods

Eighteen individuals (8 female, 30.2 ± 0.6yrs, 1.72 ± 0.11 m, 72.3 ± 14.8 kg), with no musculoskeletal injuries, provided written informed consent before participating. The research was approved by the Macquarie University Human Research Ethics Committee (HREC: 52021988028978). Participants attended three sessions over two days separated by three to seven days. Session 1 and Session 2 took place in the morning and afternoon, respectively, of the first day to test intra-day reliability. Session 3 was on day two at a similar time as Session 1 to assess inter-day reliability. In each session, participants completed a body weight squat (BWSQ) and an overhead squat (OHSQ) with no body armour (NBA) and wearing body 9 kg armour (BA9) (TacTec Plate Carrier, 5.11 Irvine, CA, USA). For each condition, participants completed each squat to their maximum depth (unrestricted-range) and to a standardised depth (fixed-range) using a plyometric box (36x36x45cm). Participants' motion was recorded using HumanTrak (VALD, V 2.7.6), a markerless motion capture system comprising 3D infrared and RGB cameras encased in a single unit (30 Hz, Azure Kinect DK, Microsoft) and software to estimate joint angles from 2D video. The version of the software at the time of this study applied machine vision to detect joint centres that were used to calculate Euclidean angles.

HumanTrak was placed facing the participant (i.e., parallel to the frontal plane) 2.5–3 m away, following the manufacturer's recommendations. Participants were positioned in the middle of a calibrated area prior to each movement (Fig. 1) then completed three BWSQ and OHSQ repetitions under each condition (NBA vs. BA9) and movement variation (unrestricted- vs. fixed-range). For the BWSQ, participants placed and maintained their hands on their hips. During the OHSQ, a dowel rod (0.5 kg) was held overhead with elbows extended and hands at a self-selected distance apart. The order of body armour condition was randomised and participants completed fixed-range prior to unrestricted-range squats.

Trunk angles were calculated from filtered joint centre position data as the angle between the vertical and a line from the middle of the neck (approximately C7) to the middle of the pelvis, projected onto the sagittal plane, by the HumanTrak software (dual-pass, fourth-order Butterworth, 8 Hz cut-off). Data quality was assessed in MATLAB (R2021a, Mathworks) and peak trunk sagittal plane flexion angles were extracted from each repetition. A single score for peak trunk flexion angle was produced as the average of the three repetitions in the BWSQ and OHSQ under each body armour condition and movement variation for each session.

Statistical analyses were conducted in jamovi (v.1.6.23). Descriptive statistics (means, minima, maxima, percentiles) were calculated for each body armour condition, movement variation, and testing session for qualitative assessment. Data were normally distributed according to the Shapiro-Wilk test. To assess intra-day reliability, results from Session 1 and Session 2 were compared. To assess inter-day reliability, results

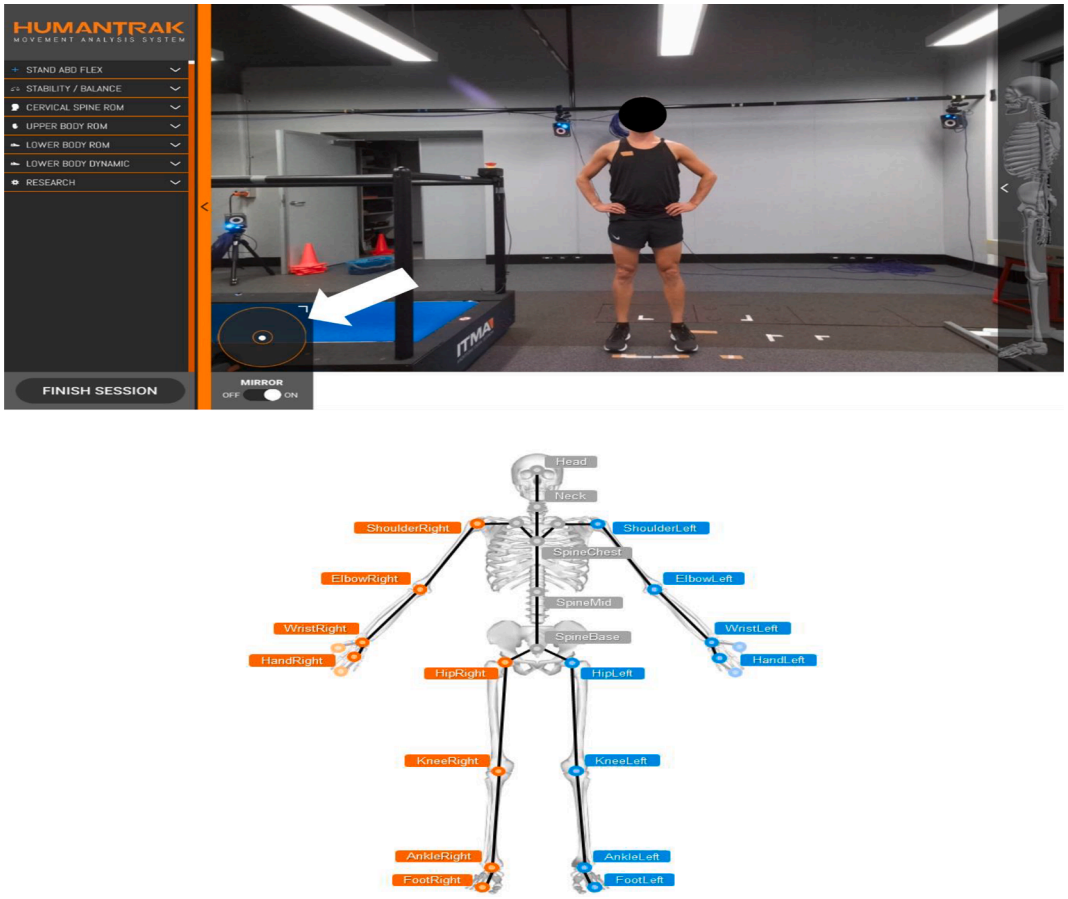


Fig. 1. Top Panel: Screenshot of the HumanTrak software with a participant standing in the middle of the camera's calibrated area (white arrow) in preparation for the body weight squat. Bottom Panel: Visualisation of the body landmarks used in HumanTrak defined by VALD Performance ().
Source: https://support.vald.com/hc/en-au/articles/5001192633881

from Session 3 were compared to Session 1. Relative reliability was evaluated using intraclass correlation (ICC) (two-way mixed effects, absolute agreement, single rater/measurement): moderate, 0.50–0.75; good, 0.75–0.90; excellent, >0.90 (Koo and Li, 2016). Pearson's correlation (*r*) was used to assess relationships between sessions: moderate, 0.30–0.50, large, 0.50–0.70, very large, 0.70–0.90, nearly perfect, >0.90 (Hopkins, 2000). Absolute reliability was evaluated using standard error of measurement (SEM) and minimal detectable change (MDC) (Weir and Vincent, 2020):

$$\boldsymbol{SEM} = \sqrt{\boldsymbol{MSE}}$$

MSE = mean square error from repeated measures ANOVA

$$\boldsymbol{MDC} = 1.96^{*}\boldsymbol{SEM}^{*}\sqrt{2}$$

2.1. Represents 95% confidence interval

Since reliability cannot be assessed with a binary decision, results from all statistics were used to develop an impression of the HumanTrak's reliability. The hypothesis was tested by comparing ICC, *r*, SEM, and MDC values between body armour conditions.

3. Results

3.1. BWSQ

Three outliers were identified in the difference scores for intra-day (Session 1 minus Session 2) and inter-day (Session 1 minus Session 3) comparisons during the unrestricted-range BWSQ with BA9. Data were not omitted because no single participant was an outlier for both comparisons. Peak trunk flexion during the BWSQ tended to be greater in the unrestricted-range (25.1°-60.6°) than fixed-range (10.4°-50.2°) variation across body armour conditions and sessions. Participants had less trunk flexion while donning body armour in the fixed-range variation (Fig. 2). With NBA, reliability was good to excellent (ICC > 0.84) with very large to nearly perfect correlations ($r > 0.80$) in both unrestricted- and fixed-range variations for intra- and inter-day comparisons (Table 1). In contrast, when body armour was donned, reliability was only moderate (ICC > 0.70) and correlations were lower, though still very large ($r > 0.60$), for the unrestricted-range variation for both comparisons. Reliability was excellent (ICC > 0.93) and correlations were nearly perfect ($r > 0.94$) in BA9 for the fixed-range variation. Relative and absolute reliability and correlations were similar between intra-day and inter-day comparisons for both body armour conditions (ICC > 0.60, SEM < 4.0°, MDC < 10.5°, $r > 0.71$). Absolute reliability was lower for NBA (SEM < 3.0°, MDC < 8.0°) than BA9 (SEM < 4.0°,

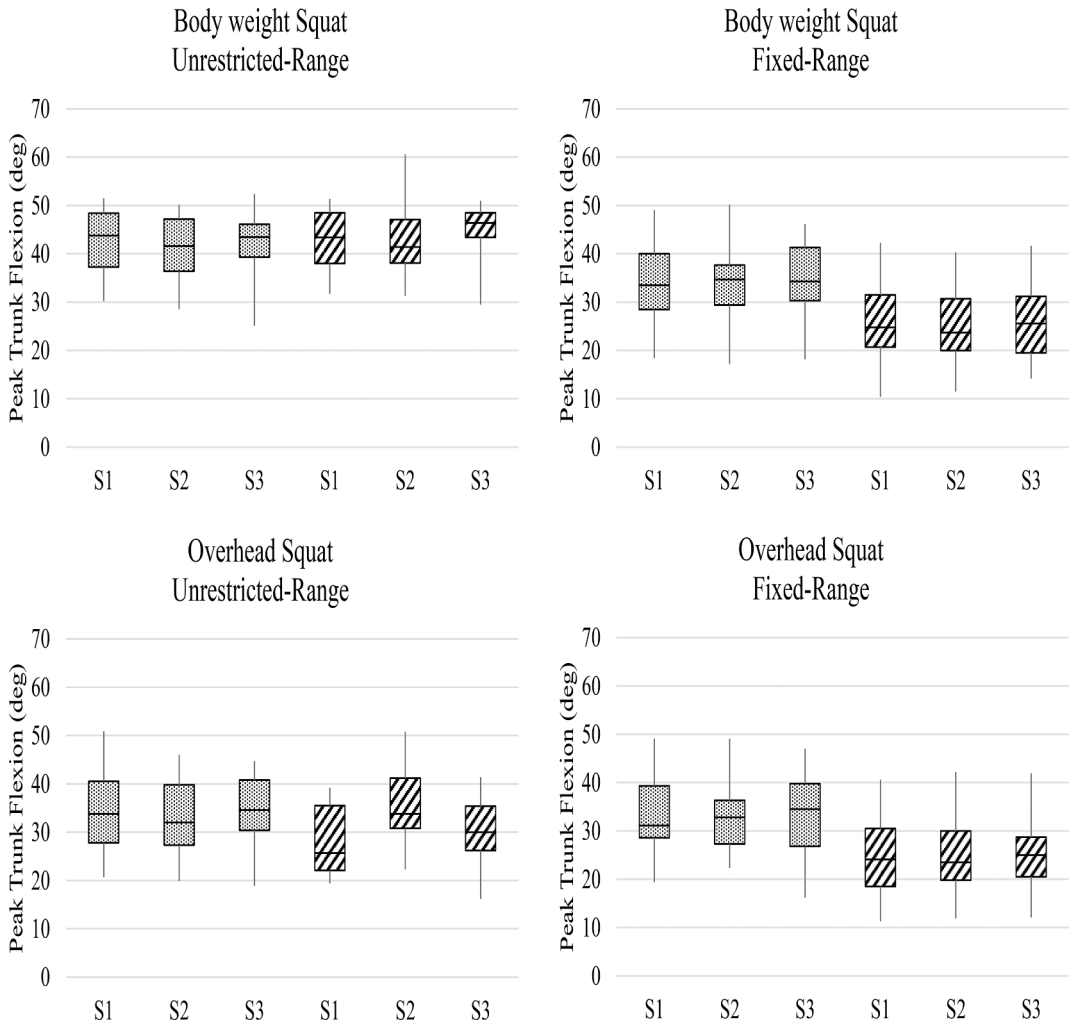


Fig. 2. Body weight squat and overhead squat peak trunk flexion angles in unrestricted- and fixed-range variations for Session 1 (S1), Session 2 (S2), and Session 3 (S3). Mean and 25th and 75th percentiles are shown in each box plot and whiskers represent minimum and maximum values. No body armour data are represented with dotted boxes and body armour with 9 kg with diagonal line boxes. NB: Figure does NOT need to appear in colour in print.

Table 1
Intraclass correlation (ICC), Pearson's correlation (*r*), standard error of measurement (SEM – in degrees and as a percentage of the group mean), and minimal detectable change (MDC – in degrees and as a percentage of the group mean) to assess intra- and inter-day reliability and the relationships of peak trunk flexion angles during the body weight squat and overhead squat between testing sessions.

				ICC	*r*	SEM		MDC	
Body Weight Squat	Unrestricted-Range	NBA	Intra	0.90	0.92*	1.97°	4.7%	5.46°	13.0%
			Inter	0.84	0.83*	2.82°	6.7%	7.81°	18.6%
		BA9	Intra	0.71	0.71*	3.61°	8.1%	10.02°	22.5%
			Inter	0.60	0.71*	3.74°	8.4%	10.36°	23.3%
	Fixed-Range	NBA	Intra	0.93	0.92*	2.37°	6.8%	6.56°	18.8%
			Inter	0.90	0.80*	2.66°	7.6%	7.38°	21.2%
		BA9	Intra	0.96	0.96*	1.90°	7.3%	5.28°	20.4%
			Inter	0.93	0.94*	2.18°	8.4%	6.03°	23.3%
Overheard Squat	Unrestricted-Range	NBA	Intra	0.95	0.96*	1.74°	5.0%	4.83°	14.0%
			Inter	0.84	0.93*	3.07°	8.9%	8.52°	24.6%
		BA9	Intra	0.92	0.92*	2.09°	6.0%	5.78°	16.6%
			Inter	0.82	0.91*	3.06°	8.8%	8.48°	24.4%
	Fixed-Range	NBA	Intra	0.91	0.92*	2.98°	9.0%	8.25°	25.0%
			Inter	0.85	0.87*	2.53°	7.7%	7.00°	21.2%
		BA9	Intra	0.91	0.91*	2.59°	10.4%	7.18°	28.8%
			Inter	0.87	0.90*	2.86°	11.5%	7.94°	31.9%

SEM = standard error of measurement.
MDC = minimal detectable change.
r = Pearson correlation, *p < 0.01.
ICC = intraclass correlation.
NBA = no body armour.
BA9 = weighted body armour (9 kg).

MDC < 10.5°) in the unrestricted-range variation, but the opposite was observed in the fixed-range variation (NBA: SEM < 3.0°, MDC < 7.5°; BA9: SEM < 2.5°, MDC < 6.5°). Overall, reliability was reduced when body armour was donned in the unrestricted-range condition but not for the fixed-range condition in the BWSQ.

3.2. OHSQ

An outlier was removed from the OHSQ NBA fixed-range data, reducing skewness from 0.56 to 0.17 and 1.3 to 0.04 in intra- and inter-day differences, respectively. Peak trunk flexion ranged from 18.9°-50.9° in the unrestricted-range and 11.3°-49.1° in fixed-range (Fig. 2). Like BWSQ, participants had less trunk flexion when donning body armour at fixed-range. In OHSQ, reliability and correlation values were similar with NBA and BA9 across variations and intra- and inter-day comparisons (Table 1). In both body armour conditions, reliability was excellent for intra-day (ICC > 0.91) and good for inter-day (ICC > 0.82). Correlations were nearly perfect for both variations and comparisons ($r > 0.91$, $p < 0.01$) except for NBA fixed-range inter-day, which was very large ($r > 0.85$, $p < 0.01$). Relative and absolute reliability and correlations in OHSQ tended to be better for intra-day (ICC > 0.91, SEM < 3.0°, MDC < 8.5°, $r > 0.91$) than inter-day (ICC > 0.82, SEM < 3.5°, MDC < 9.0°, $r > 0.87$) for both body armour conditions. Absolute reliability was similar between body armour conditions for both variations (SEM < 3.5°, MDC < 9.0°).

4. Discussion

We assessed HumanTrak's intra- and inter-day reliability for estimating peak trunk flexion during squat movements with and without body armour. HumanTrak reliability was reduced when body armour was donned during the unrestricted-range BWSQ, but overall reliability was high; therefore, our hypothesis was partially supported. Practitioners can be confident in the consistency of HumanTrak's estimates of peak trunk flexion during squat movements within and across days, regardless whether body armour is donned.

The SEM and MDC values can help practitioners determine the suitability of HumanTrak for their assessments. With a maximum SEM of 3.74° across all movements, conditions, and comparisons, trunk motion can be reliably measured on the same and different days. Changes in peak trunk flexion of 8.5° or more can be detected when body armour is not worn and 10.5° or more when body armour is donned. This reliability (ICC = 0.60–0.96) is equivalent to other markerless systems for measuring trunk sagittal plane motion in gait (ICC = 0.67–0.88 (Tamura et al., 2020)) and reaching tasks (ICC = 0.76–0.95, CV = 8.1° (Clark et al., 2012)). Notably, HumanTrak was more reliable and had lower SEM values when compared to the reliability of marker-based motion capture for assessing trunk flexion ROM (ICC = 0.56–0.78, SEM = 7.1°-7.8°) (Mousavi et al., 2018). There are no guiding values for trunk flexion to reference in the literature in relation to injury risk during a squat movement. This is likely due to the complex relationship between trunk and lower limb motion. The validity of HumanTrak must still be investigated, but these findings suggest HumanTrak can be used to reliably assess changes in maximum ROM over the course of a training programme.

Body armour impacted reliability slightly more for BWSQ than OHSQ possibly due to effects of the weighted vest on participant experience and differences in task constraints. Outliers in the unrestricted-range BWSQ with BA9 likely contributed to the greater SEM and MDC values and lower ICC and *r* values for this condition and may reflect different strategies between sessions when using BA9. Participants may have been unfamiliar with squatting when wearing a weighted vest, which could have led to increases in movement pattern variability (Coker, 2017) and reduced reliability results. In contrast, reliability and correlation scores were similar in the unrestricted-range OHSQ with and without body armour. Participants may have been more consistent in OHSQ because of more task constraints compared to the BWSQ (e.g., upper limbs in a specified position, use of an implement). The constraints in OHSQ relative to BWSQ could have caused participants to 'freeze' degrees of freedom in the OHSQ (Vereijken et al., 1992). For example, to feel like the OHSQ was executed successfully, a participant may have reduced (or 'froze') trunk flexion range to squat as deep as possible (as per the task instructions) while keeping the dowel above their head and maintaining balance. Further research could include

familiarisation to reduce the novelty of wearing body armour during the OHSQ.

The outlier in the BWSQ with no body armour appeared to be an unexplained error. This participant had a 20° discrepancy between Session 1 and Session 3 for the BWSQ with no body armour; in comparison, this participant's greatest difference between sessions was 8° across all other conditions. Practitioners are encouraged to visually inspect results from HumanTrak to help detect errors.

Intra-day was better than inter-day reliability in both squats regardless of whether body armour was worn, which was likely due to a recency effect. HumanTrak was put away after each session because the study was conducted in a shared laboratory, like a real-world setting when multiple practitioners use the same space. Regardless, HumanTrak produced reliable peak trunk flexion within and across days with and without body armour. Since the reduction in reliability was small between intra- and inter-day, careful set-up procedure standardisation likely supported consistent results. HumanTrak could provide a time-efficient strategy for evaluating joint ROM during functional squat tasks in large cohorts that can complement traditional ROM assessments, like manual goniometry. This study was limited to healthy populations. Participants may have been unfamiliar with body armour or squat variations in this study, which could have influenced reliability and correlations. Despite this limitation, the results support HumanTrak for assessing trunk motion in squats. Future research needs to validate HumanTrak against a variety of ROM measurements.

HumanTrak can be used for screening sagittal plane trunk motion during squat movements. Practitioners who wish to assess meaningful changes in sagittal plane trunk motion when body armour is worn should consider the error margins for each movement and body armour condition presented here. HumanTrak is more reliable for measurements taken on the same day than on separate days, but estimates of peak trunk flexion during squat movements are still reliable between testing days with careful standardisation of procedures.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: One of the co-authors was an employee of VALD Performance at the time this study was conducted. There was no influence from VALD Performance on the findings or interpretation of the results. This research was partially supported by the Macquarie University Research Excellence Stipend Scholarship and the VALD Performance Stipend Scholarship.

Acknowledgements

The authors thank all participants for donating their time. This research was partially supported by the Macquarie University Research Excellence Stipend Scholarship and the VALD Performance Stipend Scholarship. VALD Performance is also thanked for the in-kind supply of the HumanTrak system.

References

Bonnechère, B., Jansen, B., Salvia, P., Bouzahouene, H., Omelina, L., Moiseev, F., Sholukha, V., Cornelis, J., Rooze, M., Jan, S.V.S., 2014. Validity and reliability of the Kinect within functional assessment activities: comparison with standard stereophotogrammetry. Gait Posture 39, 593–598.

Clark, R.A., Pua, Y.-H., Fortin, K., Ritchie, C., Webster, K.E., Denehy, L., Bryant, A.L., 2012. Validity of the Microsoft Kinect for assessment of postural control. Gait Posture 36, 372–377.

Coker, C.A., 2017. Motor learning and control for practitioners. Routledge.

Colyer, S.L., Evans, M., Cosker, D.P., Salo, A.I., 2018. A review of the evolution of vision-based motion analysis and the integration of advanced computer vision methods towards developing a markerless system. Sports Medicine - Open 4, 1–15.

Cook, G., 2010. Movement: Functional movement systems: Screening, assessment. Corrective Strategies (1st ed.). Aptos, CA: On Target Publications, 73-106.

Gallagher, S., Marras, W.S., 2012. Tolerance of the lumbar spine to shear: a review and recommended exposure limits. Clin. Biomech. 27, 973–978.

Graci, V., Van Dillen, L.R., Salsich, G.B., 2012. Gender differences in trunk, pelvis and lower limb kinematics during a single leg squat. Gait Posture 36, 461–466.

Hopkins, W.G., 2000. Measures of reliability in sports medicine and science. Sports Med. 30, 1–15.

Koo, T.K., Li, M.Y., 2016. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. J. Chiropr. Med. 15, 155–163.

Kritz, M., Cronin, J., Hume, P., 2009. The bodyweight squat: A movement screen for the squat pattern. Strength Cond. J. 31, 76–85.

List, R., Gülay, T., Stoop, M., Lorenzetti, S., 2013. Kinematics of the trunk and the lower extremities during restricted and unrestricted squats. J. Strength Cond. Res. 27, 1529–1538.

Lopes, T.J.A., Ferrari, D., Ioannidis, J., Simic, M., Mícolis de Azevedo, F., Pappas, E., 2018. Reliability and validity of frontal plane kinematics of the trunk and lower extremity measured with 2-dimensional cameras during athletic tasks: a systematic review with meta-analysis. J. Orthop. Sports Phys. Ther. 48, 812–822.

Mitchell, K.B., 2017. Encumbered range of motion assessment of a novel body armor system designed to improve mobility. J. Sci. Med. Sport 20, S63.

Mitchell, K.B., 2013. Standard methodology for assessment of range of motion while wearing body armor, in: United States Department of Defense (Ed.). Army Natick Soldier Research Development and Engineering Center.

Mousavi, S.J., Tromp, R., Swann, M.C., White, A.P., Anderson, D.E., 2018. Between-session reliability of opto-electronic motion capture in measuring sagittal posture and 3-D ranges of motion of the thoracolumbar spine. J. Biomech. 79, 248–252.

Papic, C., Sanders, R.H., Naemi, R., Elipot, M., Andersen, J., 2021. Improving data acquisition speed and accuracy in sport using neural networks. J. Sports Sci. 39, 513–522.

Potvin, J., McGill, S., Norman, R., 1991a. Trunk muscle and lumbar ligament contributions to dynamic lifts with varying degrees of trunk flexion. Spine 16, 1099–1107.

Potvin, J., Norman, R., McGill, S., 1991b. Reduction in anterior shear forces on the L4L5 disc by the lumbar musculature. Clin. Biomech. 6, 88–96.

Schmitz, A., Ye, M., Boggess, G., Shapiro, R., Yang, R., Noehren, B., 2015. The measurement of in vivo joint angles during a squat using a single camera markerless motion capture system as compared to a marker based system. Gait Posture 41, 694–698.

Tamura, H., Tanaka, R., Kawanishi, H., 2020. Reliability of a markerless motion capture system to measure the trunk, hip and knee angle during walking on a flatland and a treadmill. J. Biomech. 109, 109929.

Vereijken, B., Emmerik, R.E.v., Whiting, H., Newell, K.M., 1992. Free (z) ing degrees of freedom in skill acquisition. Journal of Motor Behavior 24, 133-142.

Weir, J.P., Vincent, W.J., 2020. Statistics in kinesiology. Human Kinetics Publishers.