MARKERLESS VIDEO-BASED ESTIMATION OF 3D APPROACH VELOCITY IN THE JAVELIN THROW

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The purpose of this study was to explore the usefulness of a markerless open-source human pose estimation algorithm, for estimating centre of mass (CoM) velocity in the javelin throw at three discrete time instances: the last right leg touchdown (RLTD), brace leg touchdown (BLTD) and release. Forty throws from four right-handed javelin throwers were simultaneously captured with two high-speed video cameras and a 16-camera marker-based Vicon motion capture system. For horizontal resultant velocity (Vel_{hor}), the method demonstrated excellent validity at RLTD, whereas at BLTD and release errors were notable. Based on these findings, CoM Vel_{hor} can be estimated using the proposed method with promising accuracy at RLTD. At BLTD and release, using a CoM segment model with arms in more optimized measurement conditions might further improve the accuracy.

KEYWORDS: kinematics, motion capture, computer vision, coaching, feedback.

INTRODUCTION: The javelin throw is an athletics field event where the aim is to throw the javelin as far as possible. According to Morriss & Bartlett (1996), the most important factor affecting throw distance is the release speed of the javelin. During the run-up, the horizontal velocity of the thrower's centre of mass can be up to 7.0 m/s, which gives the javelin its initial velocity before the pull (Morriss & Bartlett, 1996). The thrower tries to maintain that velocity during the crossovers, and finally brakes against the brace leg during the delivery phase.
The current gold standard for determining the location of the human body centre of mass (CoM) in sporting events is marker-based motion capture (Linke et al., 2018). Marker data can be used to model the CoM locations of body segments and thus the whole body with high precision (Napier et al., 2020). However, marker-based motion capture is time consuming, often limited to laboratory environments, and requires expensive equipment and high-level expertise.
Recent advancements in machine learning have made automated markerless video-based pose estimation accessible for sports scientists, making it a possible solution to be used in the development of real-time feedback applications in sports. However, the precision of pose estimation is largely unknown. Therefore, the purpose of the present study was to explore the usefulness of a markerless open-source human pose estimation algorithm, namely Mediapipe BlazePose (Bazarevsky et al., 2020), for estimating centre of mass velocity in the javelin throw.

METHODS: Four right-handed international and national level javelin throwers (two men, two women; age 22.4 ± 3.7 years old) volunteered for the study. All subjects provided written informed consent. Each thrower performed a testing session in an indoor athletics hall at the Kuortane Olympic Training Center in Finland. During the session, the thrower started by performing very low intensity throws, and gradually increased the intensity. Once they felt prepared to throw at competition intensity, each thrower performed six to ten maximal throws. A total of 40 throws (some submaximal) pooled from the four throwers were used for analyses.
The reference gold standard full-body 3D motion analysis was performed using a Vicon system (Vicon Motion Systems, Oxford, UK) with 16 Vero cameras recording at 300 Hz. 45 reflective markers were attached to the thrower's body segments to create a full body model (PlugInGait FullBody Ai plus six additional markers on the medial side of the ankles, knees, and elbows so that it was possible to calculate joint centre locations for a more precise CoM location

estimation). The recorded data were auto labelled and visually verified using Vicon Nexus software version 2.11. Marker trajectory data gap filling was performed using linear interpolation. The system was calibrated as per the manufacturer's instructions. The thrower's centre of mass location (CoM_{VICON}) was calculated using the Gait2392 model (as described in a previous study by John et al. (2013), with arms and the scapulothoracic joint added) in OpenSim software version 4.3. The model was scaled individually for each thrower by body mass, preserving mass distribution. The 3D coordinates were filtered using a 4^{th} order low pass Butterworth filter (cut-off frequency 6 Hz).

To provide footage for the pose estimation algorithm, video data was captured with two high-speed video cameras (LUMIX DC-GH5S, Panasonic Corporation, Japan) at 240 Hz (shutter speed: 1/1000; FHD: 1920 x 1080). One camera was placed behind the thrower right next to the run-up lane (approximately 18 m from the foul line) facing along the throwing direction. The other camera was placed to the right side (approximately 18 m from the run-up lane) facing approximately perpendicular to the throwing direction. For each trial, data were time-synchronised between the systems using an LED light trigger signal.

Before and after the measurements, a calibration procedure was performed. Four adjustable poles with small circular reflective surfaces at both ends were positioned around the capture volume, and locations of the calibration points (the middle of each surface) were measured using a tacheometer resulting in eight known 3D coordinates. Calibration points were manually digitised from the rear and side videos to obtain calibration coordinates for each field of view using SIMI Motion software version 9.2.1 (Simi Reality Motion Systems GmbH, Unterschleissheim, Germany). Using these calibration coordinates, each individual camera's x and y coordinates were transformed to global 3D coordinates using Direct Linear Transformation (Abdel-Aziz & Karara, 1971).

For each camera view, 2D poses of the throwers were computed for each video frame using the MediaPipe BlazePose with model complexity 1 (Bazarevsky et al., 2020), as illustrated in Figure 1. CoM location was estimated ($CoM_{BLAZEPOSE}$) by applying a three-segment Dempster model (Winter, 2009) consisting of an upper body segment (hip and shoulder coordinates taken into account) and two lower extremity segments (hip and ankle coordinates taken into account). To account for mislabelling of the left versus right sides in some images, the average location of the left and right markers was used in the segment model. As the algorithm outputs coordinates normalised to image width and height, they were scaled accordingly for further analyses. These $CoM_{BLAZEPOSE}$ coordinates were first low pass filtered with a 4^{th} order Butterworth filter (cut-off frequency 16 Hz), and then input to the Direct Linear Transformation algorithm to convert them to global 3D coordinates. The 3D coordinates were further low pass filtered with a 4^{th} order Butterworth filter (cut-off frequency 6 Hz).

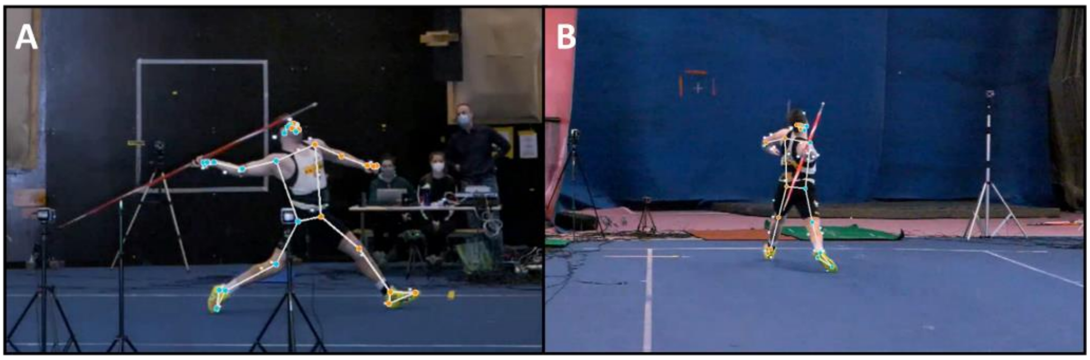

Figure 1: An example of Mediapipe BlazePose output with the pose annotation overlaid on the thrower from the side (A) and rear (B) camera views.

Horizontal resultant velocity (Vel_{hor}) was calculated from CoM_{VICON} and $CoM_{BLAZEPOSE}$ coordinates at three discrete phases: the last right leg touchdown (RLTD), brace leg touchdown (BLTD) and release. Values are reported as mean ± standard deviation where applicable. The concurrent validity of Vel_{hor} derived from $CoM_{BLAZEPOSE}$ was evaluated by using Vel_{hor} derived from CoM_{VICON} as the comparison. Mean difference (bias) evaluated with paired t-test, 95%

limits of agreement, Pearson correlation coefficient (r), root mean squared coefficient of variation percentage ($CV\%_{RMS}$), and intra-class correlation coefficient (calculated for absolute agreement, ICC) are reported to indicate validity. ICCs were used to indicate the agreement, with values of <0.40, 0.40 to <0.60, 0.60 to <0.75, and ≥0.75 representing the qualitative thresholds for poor, fair, good, and excellent levels of agreement, respectively (Cicchetti, 1994). Further, Bland-Altman plots (Bland & Altman, 1986) were used to visualise the agreement between the methods. Statistical analysis was conducted using R (version 4.0.2 (2020-06-22), https://www.R-project.org/) and the significance level was set at $p \leq 0.05$.

RESULTS: The difference between methods in Vel_{hor} (mean bias calculated as CoM_{VICON}-based minus $CoM_{BLAZEPOSE}$-based Vel_{hor}) was -0.07 m/s ($p < 0.001$) at RLTD, -0.09 m/s (not significant, ns) at BLTD, and 0.04 m/s (ns) at release (Table 1). As illustrated in Figure 2, agreement for Vel_{hor} was excellent at RLTD (ICC 0.97), BLTD (ICC 0.75) and release (ICC 0.87). $CoM_{BLAZEPOSE}$-based velocities demonstrated strong to very strong relationships with velocities derived from CoM_{VICON} (Figure 2).

Table 1: Mean ± SD and error statistics of the throwers' horizontal resultant velocity with the two methods.

	RLTD (m/s)	BLTD (m/s)	Release (m/s)
CoM_{VICON}	5.29 ± 0.49	4.84 ± 0.39	2.68 ± 0.52
$CoM_{BLAZEPOSE}$	5.36 ± 0.49	4.92 ± 0.41	2.64 ± 0.74
Bias (95% CI)	-0.07 (-0.10 to -0.04)***	-0.09 (-0.18 to 0.00)	0.04 (-0.07 to 0.15)
$CV\%_{RMS}$	1.5	4.1	9.8

CI = confidence interval, $CV\%_{RMS}$ = root-mean-squared coefficient of variation percentage, *** = $p < 0.001$

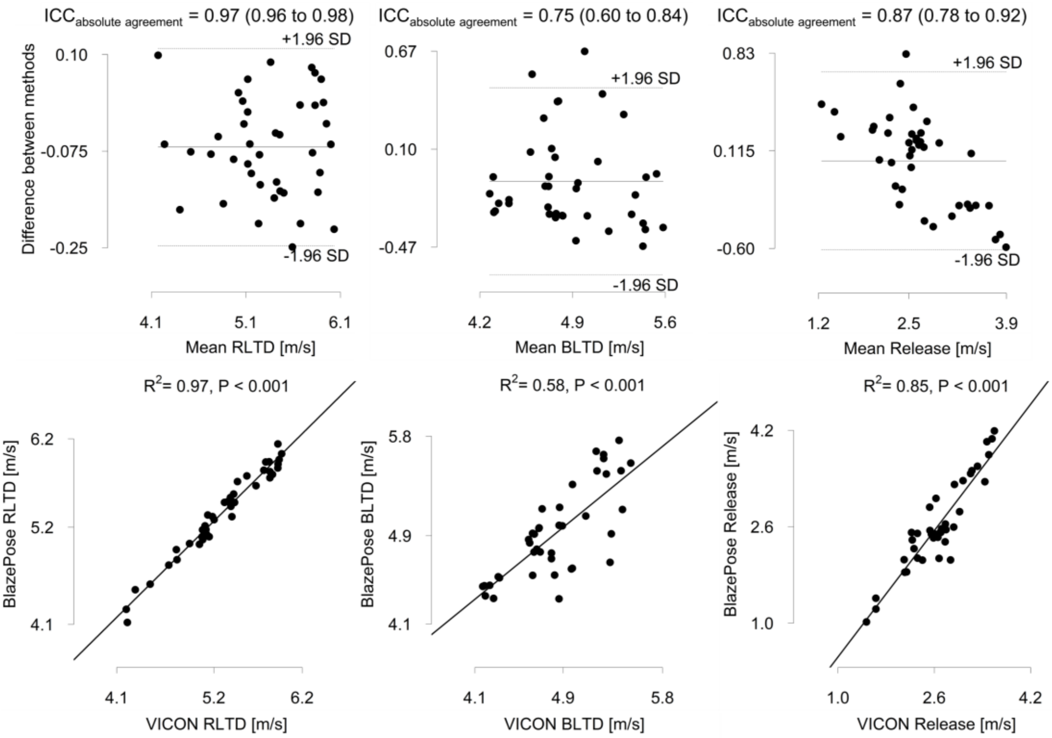

Figure 2: Bland-Altman plots (top) representing the mean bias and limits of agreement (± 1.96 × SD of differences), and correlations (bottom) between the throwers' marker-based (VICON) and markerless (BlazePose) horizontal resultant velocities at three discrete time instances. ICC = intra-class correlation coefficient (95% CI), RLTD right leg touchdown, BLTD brace leg touchdown, SD standard deviation.

DISCUSSION: Our results suggest that in the javelin throw, approximating CoM location using a three-segment model from hip, shoulder and ankle markers detected by BlazePose and further calculating Vel_{hor} is a promising method, especially at RLTD. At BLTD, the accuracy varies, and at release, Vel_{hor} is slightly underestimated at low and overestimated at high velocities.

One reason for these differences at the analysed discrete time instances may be the way CoM location was approximated, using only three segments, and especially not using the arms in the segment model. Compared to the present study, a previous study by Napier et al. (2020) observed similar agreement between CoM and a single sacral marker trajectory, especially in the anteroposterior direction, in treadmill running. However, in running the mass of the arms is always quite evenly distributed around the actual CoM. This supports our findings regarding RLTD, where the arms are outstretched on both sides of the body. Regarding BLTD and release, which occur after the thrower starts to reach forward with the brace leg and pull the javelin, the mass of the arms is no longer evenly distributed around the actual CoM. Hence, the accuracy of the method at BLTD and release could possibly be improved by using a segment model with arms to estimate CoM location.

Another reason for the weaker accuracy at BLTD and release could be the overall accuracy of the pose detection algorithm. In general, the arms were poorly detected by the algorithm, which led to the decision to exclude them from the segment model, and the left versus right sides were mislabelled in some images. Camera positioning, the appearance of multiple people in the background in some images, and the challenging indoor environment may also have contributed to algorithm performance.

As calibration is the only phase that requires manual work and the necessary algorithms can be run with very little delay automatically after each throw, the proposed method could be almost fully automated to provide rapid feedback of the thrower's approach velocity in training sessions. The setup is also relatively easy for coaches or sports scientists with little experience of such methods and could be potentially done in a few minutes, as it only requires cameras to be positioned and calibration to be run.

CONCLUSION: CoM horizontal resultant velocity can be estimated using the proposed method with promising accuracy at RLTD. At BLTD and release, using a CoM segment model with arms in more optimized measurement conditions might further improve the accuracy. This method could be used to provide rapid feedback about approach velocity during training.

REFERENCES

Abdel-Aziz, Y.I. & Karara, H.M. (1971). Direct Linear Transformation from Comparator Coordinates into Object Space Coordinates in Close-Range Photogrammetry. *Photogrammetric Engineering and Remote Sensing*, 81, 103-107.

Bazarevsky, V., Grishchenko, I., Raveendran, K., Zhu, T., Zhang, F. & Grundmann, M. (2020). BlazePose: On-device Real-time Body Pose tracking. *http://arxiv.org/abs/2006.10204*.

Bland, J. M. & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet (London, England)*, *1*(8476), 307–310.

Cicchetti, D. V. (1994). Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. *Psychological Assessment*, *6*(4), 284–290.

John, C. T., Anderson, F. C., Higginson, J. S. & Delp, S. L. (2013). Stabilisation of walking by intrinsic muscle properties revealed in a three-dimensional muscle-driven simulation. *Computer Methods in Biomechanics and Biomedical Engineering*, *16*(4), 451–462.

Linke, D., Link, D. & Lames, M. (2018). Validation of electronic performance and tracking systems EPTS under field conditions. *PLOS ONE*, *13*(7), e0199519.

Morriss, C. & Bartlett, R. (1996). Biomechanical Factors Critical for Performance in the Men's Javelin Throw. *Sports Medicine*, *21*(6), 438–446.

Napier, C., Jiang, X., MacLean, C. L., Menon, C. & Hunt, M. A. (2020). The use of a single sacral marker method to approximate the centre of mass trajectory during treadmill running. *Journal of Biomechanics*, *108*, 109886.

Winter, D. A. (2009). Segment Mass and Center of Mass. In Biomechanics and Motor Control of Human Movement (4th edition, pp. 83–95). John Wiley & Sons, Inc. Hoboken, New Jersey.