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# Are action sport cameras accurate enough for 3D motion analysis? A comparison with a commercial motion capture system

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**Running title:** Accuracy of the action sport cameras and commercial system

**Are action sport cameras accurate enough for 3D motion analysis? A comparison with a commercial motion capture system**

**Abstract**

The aim of this study was to assess the precision and accuracy of an Action Sport Camera (ASC) system (4 GoPro Hero3+ Black) by comparison with a commercial motion capture (MOCAP) system (4 ViconMX40). Both systems were calibrated using the MOCAP protocol and the 3D markers coordinates of a T-shaped tool were reconstructed, concurrently. The 3D precision was evaluated by the differences in the reconstructed position using a Bland-Altman test, while accuracy was assessed by a rigid bar test (Wilcoxon rank sum). To examine the accuracy of the ASC in respect to the knee flexion angles, a jump and gait task were also examined using one subject (Wilcoxon rank sum). The ASC system provided a maximum error of 2.47 mm, about 10 times higher than the MOCAP (0.21 mm). The reconstructed knee flexion angles were highly correlated ($r^2>0.99$) and showed no significant differences between systems (<2.5°; $p>0.05$). As expected, the MOCAP obtained better 3D precision and accuracy. However, we show such differences have little practical effect on reconstructed 3D kinematics.

***Keywords: System Comparison, Precision, Accuracy***

**Word Count: 2061**

## Introduction

Optoelectronic motion capture systems (MOCAP), such as Vicon (Oxford Metrics Ltd., UK), Elite (BTS, Milan, Italy), Qualysis (Göteborg, Sweden), Motion Analysis (Motion Analysis Corp., Santa Rosa, CA, USA) and Optitrack (Natural Point Inc. Corvallis, OR), are considered to be the traditional apparatuses to quantitatively measure and analyze the three-dimensional (3D) human segmental motion in clinics, sports and the entertainment industry. They all use retroreflective markers attached to the body's surface and infra-red strobes, combined with camera lenses and sensors, to collect the 3D position of markers on the limbs, which are used in the computation of body segment and joint kinematics. Despite their high 3D reconstruction accuracy (1:10000),[1,2,3] usually expressed by the ratio between 3D marker reconstruction error and the size of the working volume,[1] their high-cost is a critical factor when deciding to purchase new equipment for biomechanics analysis laboratory.[4] Consumer,[5,6] industrial[7,8] and entertainment[9,10,11] video systems are viable alternatives for motion analysis. Recent technical improvements in image resolution and capture frequency, and decreasing costs have made action sport cameras (ASC) an emerging tool in the athletic performance evaluation. This interest has been further motivated by the fact that ASC are portable and include many convenient features (e.g. waterproof, wireless operation and synchronization), which make ASC systems adaptable to different environments. Based on the idea that this technology could be a potential tool to a moving camera system, capable of acquiring data out and underwater for 3D swimming analysis, our research group has extensively addressed reconstruction accuracy.[12,13,14] Accuracy less than 3 mm, ranging from 1:2000 to 1:7000[13,14] in-air and underwater static conditions, are evidence to suggest that ASC systems perform comparatively with MOCAP systems for such 3D analysis. However, at the present time, no concurrent comparisons between ASC and MOCAP systems have been performed, through simultaneous acquisitions based on the same calibration procedure. As such, in this study we compared a GoPro camera system (ASC) to a Vicon camera system (MOCAP) in terms of 3D precision, accuracy, and kinematics of gait and jump in a controlled laboratory setup.

## Methods

As camera systems we used four GoPro Hero3+ Black (GoPro, Ca, USA) and four ViconMX40 (Vicon, Oxford Metrics Ltd., UK). The acquisition frequency was set to 120 Hz for both systems (Figure 1A). The MOCAP cameras were placed at the corners of the rectangle encircling the working volume (approximately 4.0 x 1.5 x 2.0 m, the typical size for gait analysis). To ensure a close proximity between camera pairs, ASC were hung to the MOCAP ones by means of clamp tripods. The time synchronization between systems was done by acquiring a light flashing at the very beginning of each video acquisition. To increase image-to-background contrast of the markers on ASC, each camera was equipped with a custom illumination ring consisting of four ultra-bright white LEDs featuring an overall power of about 1 watt.

For the calibration of the ASC, we used the same calibration protocol of the MOCAP (Vicon T-shape wand tool, carrying five 14 mm (Ø) passive markers). The procedure involved first the acquisition of the tool in several locations and orientations within the working volume (dynamic step). Second, the tool was recorded steady on the floor, approximately in the center of the working volume, to define the coordinate system of the calibration volume (static step). The output videos of the ASC acquisition were converted into AVI movie format by means of GoPro studio software to allow image processing for centroid marker detection. This was based on robust circle fitting and was performed by a custom software platform[13] developed in Matlab® 2015 suite (Mathworks, Natick MA).

To accommodate the MOCAP protocol of data calibration acquisition, we developed a custom two-stage procedure for ASC calibration (Figure 1B). The markers acquired from the acquisition of both static and dynamic step were used to compute a preliminary estimation of the camera parameters based on epipolar geometry.[15] This method involved four sub-steps. First, the markers acquired on the dynamic step were used to determine the intrinsic and extrinsic camera parameters of one stereo-pair, having the maximum inter-distance and the best intersection angle. Second, the markers on the static step were reconstructed in 3D and referred to the stereo-pair coordinate system. Third, such coordinates were used to build a 3D coordinate system on the floor (world reference frame), which the stereo-pair coordinate system was refereed to. Fourth, the markers on the dynamic step were reconstructed in the world reference frame. In the second stage of the calibration, all the four cameras were calibrated exploiting the 2D/3D correspondence of the reconstructed tool markers. The Direct Linear Transformation method provided an initial estimation of intrinsic and extrinsic camera parameters, disregarding optical distortions.[7] Then, the camera position and orientation were refined into a bundle adjustment approach minimizing the 2D projection error on all the cameras concurrently.[13] Since the ASC were set as a narrow field of view, the optical distortion was taken into account by adding one radial parameter into the camera model. This distortion model was considered by the fact that while higher order distortion models can, in principle, better fit the optical aberration near the lens edge, one could experience overfitting close to the image center where radial and decentering distortions have little influence on the image quality.

### Insert Figure 1 ###

By assuming the MOCAP as reference, the comparison between ASC and MOCAP was performed according to: 1) precision of the 3D reconstruction; 2) accuracy of the 3D reconstruction; 3) axis skewness in the reconstructed space; 4) kinematic data agreement for two prototypical motion patterns, namely gait and jump.

The precision of the 3D reconstruction was assessed in terms of the difference between the 3D coordinates of the three markers, placed on the tool, acquired for 10 seconds when moved within the working volume and reconstructed by the two systems concurrently. Two consecutive acquisition trials were performed. The corresponding reconstructed coordinate trajectories were compared by evaluating the Bland and Altman test (average agreement [Δ] and 95% confidence interval [C.I.] values) to assess the degree of agreement between measurements of both systems.[16] Because of the non-normality of the distributions of the difference in each 3D coordinate data (Lilliefors test) the statistical difference between each 3D coordinate obtained by MOCAP and ASC against zero was evaluated using the Wilcoxon signed rank test ($p<0.05$). In addition, the Pearson correlation coefficient ($r^2$) was used to verify the strength of the relationship between the measurements of the two systems.[17]

The accuracy of the 3D reconstruction was evaluated by analyzing two marker inter-distances (D1: 160 mm, D2: 240 mm) reconstructed from three markers on the T-shape tool. From the reconstructed distance distributions $\{D1\}_i$, $\{D2\}_i$, (where the lower index $i$ indicates the video system, ASC/MOCAP), the following quantities were computed for both systems: a) mean of the distance error distribution (ME); b) the standard deviation of the distance error distribution (SD); c) the mean absolute value of the distance error distribution (MAE) to quantify the overall accuracy of the reconstruction. Because of non-normality of error distributions (Lilliefors test), the error distributions between ASC and MOCAP were compared using a non-parametric test (Wilcoxon rank sum) with assumed statistical significance of $p<0.05$.

The axis skewness in the reconstructed space, measured by the angular deformation of the coordinate system, that was quantified by means of the angle shaped between the same three markers on the T-shape, was exploited to evaluate the accuracy above. The nominal value of the angle was 90° (manufacturing precision provided by Vicon system). The results for angle reconstruction were reported in terms of mean and standard deviation.

To evaluate the kinematic data agreement one subject (female, 32 years old, 1.7 m tall, and 58.5 kg) performed three walking trials and one countermovement jump trial. Each walk task included one gait cycle for right and one gait cycle for left limb, performed to a self-selected speed. Four markers, located at the anterior and posterior superior iliac spines, accounted for pelvis kinematics. For both lower limbs, three markers, placed at femur greater trochanter, femur lateral epicondyle and fibula lateral malleolus, described the flexion-extension angle of the knee. For the spatial parameters of the gait, the markers were located on 5$^{th}$ metatarsus and calcaneus. The trials were acquired concurrently by both systems. The reconstructed 3D coordinates underwent pre-processing by means of a 15 Hz cut-off Butterworth filter.[18] The following angular and linear gait parameters were calculated for both limbs: 1) knee flexion-extension angle as a function of time; 2) maximum knee angle; 3) the gait velocity monitored by the mean point of the pelvis markers as a function of time; 4) mean velocity; 5) stride length. For the jump trial, we calculated: 1) knee flexion-extension angle as a function of time; 2) maximum knee angle; 3) jump height, as the difference between vertical maximum and rest positions of the mean point of the pelvis markers. To evaluate the absolute difference of the knee flexion-extension angle obtained by each system we calculate the root mean square (RMS) for gait and jump tasks. For the statistical comparison of the result agreement between the two systems, in the gait and jump trials, we analyzed the patterns of the knee flexion-extension angle as a function of the time, by the Pearson correlation coefficient ($r^2$) and we also used a Wilcoxon rank sum test. To compare the stride length, we also used a Wilcoxon rank sum test since we have a sample size (one subject) and one gait cycle per trial.

## Results

The comparison of the 3D reconstruction obtained with both methods presented the absolute average agreement values (bias) ranged from 0.16 mm to 2.5 mm, the confidence interval sizes (CI) ranged from -10 mm to 11 mm and high correlation values ($r^2$>0.99). Small bias (<3 mm) were found between the two systems when we compared the coordinates of the three markers reconstructed of the T-shape tool. However, the agreement was considerable spread around some values (Figure 2A and 2B). We found that the three different distributions (X, Y and Z) were statistically different between the two systems.

### Insert Figure 2 ###

In the accuracy of the 3D reconstruction the mean absolute value of the distance error distribution of the ASC were lower than 2.5 mm and the value for MOCAP lower than 0.3 mm (Figure 3A). In both acquisitions, the mean absolute value of the distance error distribution of D1 and D2 was significantly lower for MOCAP than the ASC ($p$=0.001, Figure 3A). An example of the mean absolute error distribution during the whole acquisition for both systems in one trial is illustrated in the (Figure 3B).

Both systems provided angle results very close to 90° (ASC: 90.13±0.7° and MOCAP 89.54±0.12°, trial 1 and ASC: 89.54±0.8° and MOCAP 89.54±0.07°, trial 2). The comparison between the two systems demonstrated a significant statistical difference for trial 1 ($p$=0.001), while trial 2 did not ($p$=0.07) (Figure 3C).

### Insert Figure 3 ###

The stride length was not significantly different ($p$>0.700) between both systems and the mean gait velocity, the maximum knee angle in gait and jump and the jump height were similar (Figure 4A). As a main finding of the evaluation of the kinematic data agreement, the waveform of the knee flexion-extension angle presented high correlation values ($r^2$>0.99) and were not significantly different ($p$>0.069) between the systems in gait and jumping tasks (Figure 4B). Besides that, the RMS of the knee flexion-extension angle for the gait ranged from 1° to 1.25° to the right knee and 0.84° to 1.45° to the left knee. In the jump trial the RMS ranged from 1.83° to 3.47°.

### Insert Figure 4 ###

## Discussion

This study performed a comparison between one optoelectronic motion capture system and one custom video-based system. Values of average precision lower than 3 mm were found, nonetheless, these values were statistically significant. High correlation values were found between the two systems (see Figure 2A). A positive linear correlation was found between each system's Z coordinate data (see Figure 2B, lowest right panel). This suggested a systematic difference between ASC and MOCAP data reconstruction. This systematic error and the agreement of the ASC to the MOCAP can be influenced by many factors. An improvement in some steps of the acquisition and analysis process using the ASC, such as the usage of larger markers, better illumination to provide a higher marker to background contrast, circle fitting in the data processing, the distortion correction model and shutter speed tuning, could reduce this systematic error.

As far as 3D accuracy is concerned, errors below 0.3 mm were found by the MOCAP (see Figure 3A). These systems have sophisticated and proprietary image processing technology that gives it high accuracy.[19] The mean absolute value of the distance error distribution values found for ASC were bigger. Regarding the inter-markers length D1, the results highlighted an error ten times bigger than the MOCAP. For the inter-markers length D2, this difference of results decreases, and the error was reported eight times greater. Despite the difference between the two systems, the findings are in agreement with the values reported in other studies.[2,3,13,20] The evaluation of the angle between the three markers presented similar results for both systems. Based on the statistical analysis alone, it is difficult to conclude the presence or absence of axis skewness between systems. The literature reports a difference of 0.40° (SD 0.05°) between the angular values measured by video-based camera system and the reference value (90°).[21] In this study, we found (ASC system) a difference of 0.13° (SD 0.70°) in the first trial and 0.46° (SD 0.80°) in the second trial.

As far as kinematic measurement of the gait and jump is concerned, no significant differences were found between the systems and the trials (see Figure 4). Related to the gait trials, the maximal error between the maximum knee angles was less than 2.5° and the error on stride length was less than 2 cm between ACS and MOCAP. The volunteer performed the gait in a slow speed and the linear and angular parameters calculated were comparable with the reference values for her respective age.[22,23] Related to the jump trial, the maximal error between the maximum knee angles was less than 4.5° and the error of the jump height was less than 0.2 cm between ACS and MOCAP.

In a previous comparison of a MOCAP system to a low-cost system (Kinect),[24] a very low correlation ($r^2 < 0.30$) and errors higher than 35° for the knee maximum angle during gait were found.[25] We highlight their error findings were fourteen times larger than this work ($r^2>0.99$, average error 2.3°), which is a striking difference between these two technologies. The skin artifact can produce errors in the range of 20 mm in lower limbs during gait,[26] since this error is approximately ten times bigger than the ASC precision error found in this work we could suggest that this error is negligible for human 3D kinematic analysis.

In this study, we adopted four cameras and only one testing subject. However, the aim was to examine the potential of the gait and jump kinematics assessment and not an extensive validation. In future works, a setup with more cameras and more subjects will be implemented to explore the ASC validity in the context of whole body 3D kinematic data.

Optoelectronic MOCAP systems are meant to be state-of-the art technologies for the estimation of 3D human kinematics with a high precision. With this paper, we contributed to propose ASC as an alternative to such systems showing that they can be feasible for applications in biomechanics. While bias was apparent in the marker reconstruction precision and accuracy, this did not affect the kinematic calculations as much as expected. This means that the ASC system has the potential to analyze human movement.

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## Figures Captions

**Figure 1 –** (A) Comparison of the system setups. (B) Camera calibration working flow. (C) Wand tool used in the calibration procedure of both systems.

**Figure 2 –** (A) Correlation coefficient ($r^2$) and Bland-Altman results (bias, CI (95% confidence interval values) of the degree of agreement between MOCAP and ASC measurements through the acquisition of the L-shaped tool with the three markers (P1, P2, P3) and the *p*-values of the statistical difference between the difference in each 3D coordinate data. (B) Scatter plot with representation of the limits of agreement (Bland-Altman) of the X (left), Y (middle) and Z (right) coordinate of the P3. ASC - Action Sport Cameras. MOCAP - Motion capture system. Δ – Average agreement (continuous line). CI – 95% confidence interval values (dashed line).

**Figure 3** – (A) Results of the two acquisitions of L-shaped tool with three markers. Distance 1 (between the points P1 and P2): 160 mm. Distance 2 (between the points P2 and P3): 240 mm. *$p<0.05$. (B) Error distribution of the two distances D1 and D2 during about 10 seconds of one acquisition trial. ASC - Action Sport Cameras (continuous line) and MOCAP - Motion capture system (dashed line). (C) Angle values distribution calculated between the three points of T-shape tool during about 10 seconds of one acquisition trial. ASC - Action Sport Cameras (continuous line) and MOCAP - Motion capture system (dashed line). EV – Expected value, ME - mean of the distance error distribution, SD - the standard deviation of the distance error distribution and MAE - mean absolute value of the distance error distribution.

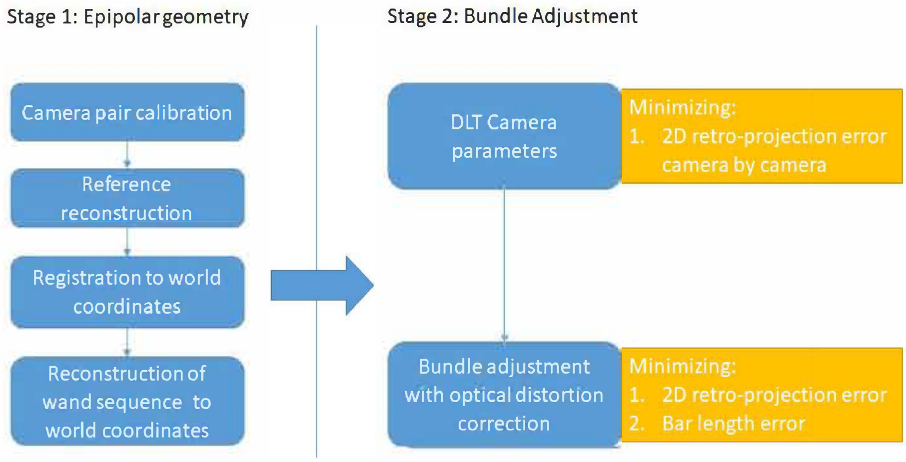
**Figure 4** – (A) Comparison of the results between ASC and MOCAP of the gait: right and left knee angle, stride length, gait velocity and the difference between the mean values of the three trials. Comparisons of the results between ASC and MOCAP of the jump: right and left knee angle and jump height. (B) The knee flexion-extension angle as a function of time for

the gait and jump trial, obtained for the ASC (continuous line) and MOCAP system (dashed line). $\Delta$ – Difference between the mean values obtained by ASC and MOCAP.

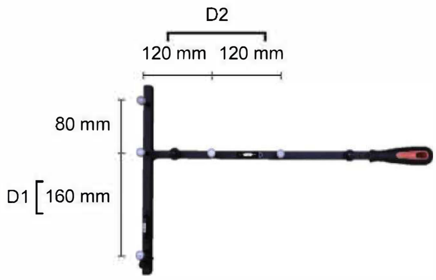
(A)

| | ASC | MOCAP |
|---|---|---|
| Camera | Video | Optoelectronic |
| Number of Cameras | 4 | 4 |
| Image Resolution [pixels] | 1280x720 | 2353x1728 |
| Acquisition Frequency [Hz] | 120 | 120 |
| Illumination | Ring with 4 LEDs | Ring with 320 LEDs |
| Calibration tool | Vicon T-shape | Vicon T-shape |
| Marker size | 14 mm Ø | 14 mm Ø |
| Calibration data acquisition | Vicon protocol | Vicon protocol |

(B)




(C)



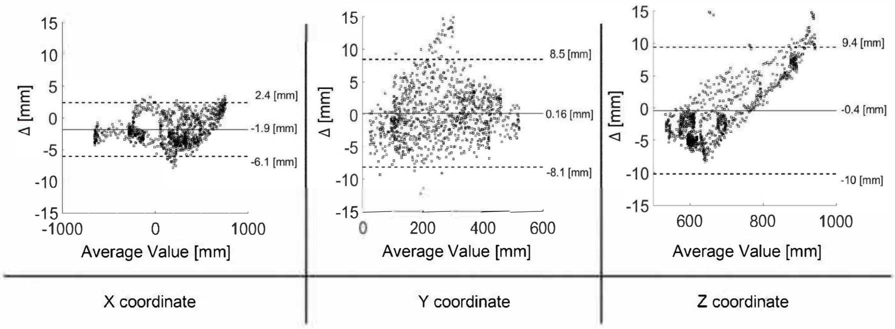

(A) Comparison of the system setups. (B) Camera calibration working flow. (C) Wand tool used in the calibration procedure of both systems.

167x198mm (600 x 600 DPI)

(A)

| | | Trial 1 | | | | Trial 2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $r^2$ | bias | CI | $p$ | $r^2$ | bias | CI | $p$ |
| P1 | x | 0.99 | -0.49 | -5.2 to 4.3 | < .001 | 0.99 | -0.93 | -4.9 to 3 | < .001 |
| | y | 0.99 | 1.20 | -6.5 to 8.9 | < .001 | 0.99 | 1.20 | -7.4 to 9.7 | < .001 |
| | z | 0.99 | 1.70 | -7.5 to 11 | < .001 | 0.99 | 1.90 | -3.1 to 7 | < .001 |
| P2 | x | 0.99 | -0.34 | -5.8 to 5.1 | < .001 | 0.99 | -1.60 | -5.4 to 2.3 | < .001 |
| | y | 0.99 | -1.40 | -8.7 to 5.9 | < .001 | 0.99 | -1.90 | -9.5 to 5.7 | < .001 |
| | z | 0.99 | -1.30 | -12 to 8.9 | < .001 | 0.99 | -1.50 | -6.5 to 3.6 | < .001 |
| P3 | x | 0.99 | -1.90 | -6.1 to 2.4 | < .001 | 0.99 | -2.50 | -7.7 to 2.7 | < .001 |
| | y | 0.99 | 0.16 | -8.1 to 8.5 | 0.26 | 0.99 | 0.70 | -7.9 to 9.2 | < .001 |
| | z | 0.99 | -0.40 | -10 to 9.4 | < .001 | 0.99 | -0.46 | -5.4 to 4.5 | < .001 |

(B)

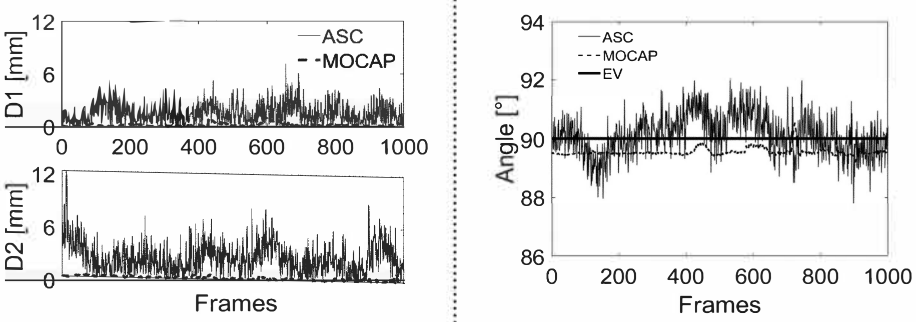



(A) Correlation coefficient ($r^2$) and Bland-Altman results (bias, CI (95% confidence interval values) of the degree of agreement between MOCAP and ASC measurements through the acquisition of the L-shaped tool with the three markers (P1, P2, P3) and the p-values of the statistical difference between the difference in each 3D coordinate data. (B) Scatter plot with representation of the limits of agreement (Bland-Altman) of the X (left), Y (middle) and Z (right) coordinate of the P3. ASC - Action Sport Cameras. MOCAP - Motion capture system. Δ – Average agreement (continuous line). CI – 95% confidence interval values (dashed line).

116x86mm (600 x 600 DPI)

(A)

| | | ASC | | | MOCAP | | |
|---|---|---|---|---|---|---|---|
| | | ME | SD | MAE | ME | SD | MAE |
| Trial 1 | D1* | -2.15 | 2.10 | 2.47 | 0.06 | 0.28 | 0.17 |
| | D2* | 0.60 | 1.82 | 1.53 | 0.01 | 0.27 | 0.18 |
| Trial 2 | D1* | -2.23 | 2.68 | 2.62 | 0.11 | 0.25 | 0.21 |
| | D2* | 1.63 | 2.04 | 2.02 | 0.11 | 0.16 | 0.16 |




(B) (C)

(A) Results of the two acquisitions of L-shaped tool with three markers. Distance 1 (between the points P1 and P2): 160mm. Distance 2 (between the points P2 and P3): 240mm. *$p<0.05$. (B) Error distribution of the two distances D1 and D2 during about 10 seconds of one acquisition trial. ASC - Action Sport Cameras (continuous line) and MOCAP - Motion capture system (dashed line). (C) Angle values distribution calculated between the three points of T-shape tool during about 10 seconds of one acquisition trial. ASC - Action Sport Cameras (continuous line) and MOCAP - Motion capture system (dashed line). EV – Expected value.

111x83mm (600 x 600 DPI)

(A)

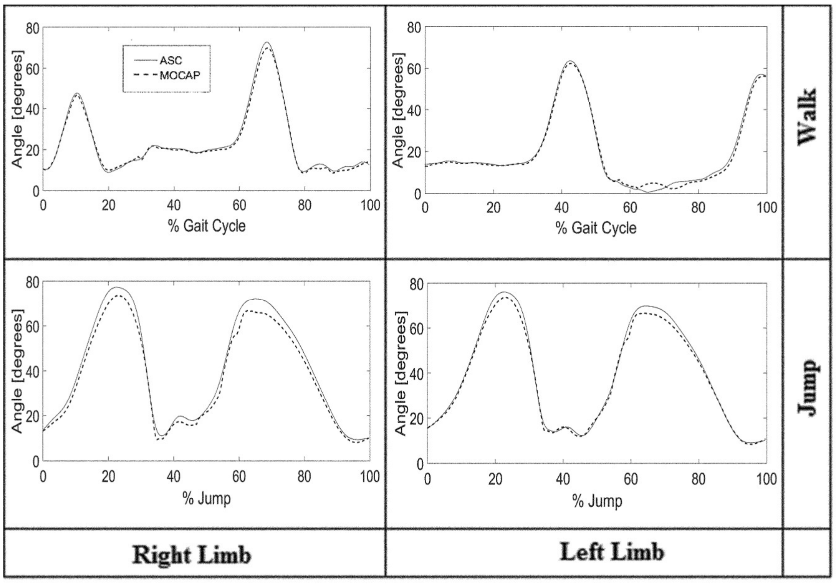
**Gait variables**

| | Stride length [m] | | | | Maximum Knee Angle [°] | | | | Gait Velocity [m/s] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Right | | Left | | Right | | Left | | | |
| Trial | ASC | MOCAP | ASC | MOCAP | ASC | MOCAP | ASC | MOCAP | ASC | MOCAP |
| 1 | 1.06 | 1.08 | 1.23 | 1.26 | 71.2 | 69.7 | 67.5 | 65.6 | 0.69 | 0.70 |
| 2 | 1.02 | 1.03 | 1.13 | 1.11 | 72.7 | 69.9 | 63.6 | 62.4 | 0.60 | 0.61 |
| 3 | 0.95 | 0.96 | 1.15 | 1.17 | 68.7 | 66.2 | 60.7 | 59.1 | 0.60 | 0.61 |
| Δ | -0.015 | | -0.01 | | 2.3 | | 1.6 | | -0.03 | |
| | *p*-value | | | | | | | | | |
| | 0.700 | | 0.999 | | | | | | | |

**Jump Variables**

| Maximum Knee Angle [°] | | | | Height [m] | |
|---|---|---|---|---|---|
| Right | | Left | | | |
| ASC | MOCAP | ASC | MOCAP | ASC | MOCAP |
| 77.3 | 72.9 | 76.1 | 73.0 | 0.23 | 0.24 |

(B)




(A) Comparison of the results between ASC and MOCAP of the gait: right and left knee angle, stride length, gait velocity and the difference between the mean values of the three trials. Comparisons of the results between ASC and MOCAP of the jump: right and left knee angle and jump height. (B) The knee flexion-extension angle as a function of time for the gait and jump trial, obtained for the ASC (continuous line) and MOCAP system (dashed line).

174x195mm (600 x 600 DPI)