EVALUATION OF SILHOUETTE-BASED MARKERLESS TRACKING FOR KINEMATICS IN SPORT

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The purpose of this study was to evaluate markerless, silhouette-based tracking for different applications in sports science. Data of segment center of gravity locations, joint center locations as well as joint angles were taken into account. To quantify the accuracy of silhouette-based in comparison to marker-based tracking, all mentioned parameters were compared with the correlation coefficient and standard deviation of the differences for three classes of movements: specific joint movements, complex movements, and highly dynamic movements (with racquet). Very strong correlations result for the segment center of gravity locations, the joint center locations as well as for joint angles in the sagittal plane except the elbow joints. Joint angle accuracy impairs in the transversal and the frontal plane with an increasing complexity and speed in the movement patterns. To obtain accurate joint angles separated into the three body planes, however, we recommend to enhance the tracking of segment rotations should be stabilized by additional information (e.g. marker or IMU).

KEY WORDS: markerless tracking, silhouette-based tracking, kinematic, motion analysis, motion capture

INTRODUCTION: “The testing and monitoring of elite athletes in their natural training environment is a relatively new area of development” (James, 2006). State of the art for motion analysis in sports science is marker tracking with stereophotogrammetry based on a video image or infrared. This method includes several problems such as soft tissue artifact (Leardini, Chiari, Croce, & Cappozzo, 2005), displacement of markers (Karlsson & Lundberg, 1994), and alteration of motion patterns caused by the attached markers (Mündermann, Corazza, & Andriacchi, 2006). Besides these problems concerning the measurement accuracy, the laboratory measurement environment required for this method contradicts the demand of a biomechanical analysis close to regular training or competition. Therefore, markerless video-based tracking is seen as a potential method to make movement analysis quicker, simpler, easier to conduct, and closer to the athlete’s familiar surroundings. Since this technology is still new for the application in the fields of sports, markerless systems have to be evaluated for sufficient accuracy. Few scientific work is done in the development and realization of silhouette-based tracking in gait analysis (Corazza, Mündermann, Gambaretto, Ferrigno, & Andriacchi, 2009; Oberländer & Brüggemann, 2011), but almost all of these investigations were carried out for the lower extremities, only for gait, and based on a general validation on the accuracy of joint center locations. No general evaluation of silhouette-based tracking which takes all relevant kinematic parameters into account was conducted so far. The purpose of this study was therefore to assess the accuracy of the new silhouette-based tracking software Simi Shape compared to the “goldstandard” marker-based tracking.

METHOD: Eight synchronized highspeed color cameras with ring lights were used for this survey. All movements were recorded with Simi Motion 3D (Simi Reality Motion Systems GmbH, Unterschleißheim, Germany), which was also used for the marker-based tracking. Silhouette-based tracking was carried out with the software Simi Shape. Data of all trials were given as results of inverse kinematics models included in this software. Each recording could be analyzed with both tracking methods.

All movements were performed by one subject. Three different classes of movements were assessed.

1. *Specific joint movements:*
   Eleven movements were recorded for the hip, knee, ankle, shoulder and elbow joint of both body sides performed in a small and big range motion, respectively. All in all, 44 movements with 595 ± 129 frames in each case were conducted.

2. *Complex movements:*
   Twelve complex movements were analyzed, seven with a full body marker set (biking on stationary bike, running with big steps, running with small steps, kicks and box punches, jumps on both legs, jumps on the right leg, jumps on the left leg) and five with lower body marker set (jumping jack, jumps on both legs, jumps on the left leg, jumps on the right leg, jumps on alternating legs) with 278 ± 229 frames in each case.

3. *Highly dynamic movements (tennis):*
   Four different tennis strokes performed at the baseline of the tennis court were included in this study: serve (555 frames), forehand (385 frames), one-handed backhand (365 frames) and two-handed backhand (335 frames).

The specific joint movements as well as the complex movements were recorded with a sampling rate of 100 Hz and a resolution of 0.3 Megapixel in a laboratory environment, tennis strokes with a resolution of 1024x1024 pixels and sampling rate of 250 Hz due to high movement velocity.
The locations of 14 segment centers of gravity (SegCOG) as well as the overall body center of gravity (COG) were traced of all mentioned movements. Furthermore, joint angles (JAng - separated into the three body planes) and joint center locations (JC) were recorded and assessed in a specific manner: shoulder, hip and ankle joints are modeled as a ball-joint with three rotational degrees of freedom, whereas knee and elbow joints are modeled as a hinge joint (one rotational degree of freedom = flexion / extension).
To quantify the accuracy of markerless tracking in comparison to marker-based tracking, a multi-stage statistical procedure was used including the empirical correlation coefficient

$$r := \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \in [1; -1]$$

, the standard deviation of the differences between markerless and marker-based data (SD_{diff}) and the gradient (a_1) of the linear-polynomial fit ($f(x) = a_1x + a_0$) as a result of simple linear regression. The interpretation of the correlation coefficient is presented in Table 1.

Table 1
Interpretation of the correlation coefficient (Landis et al., 1977)

Correlation	Interpretation
r ≥ 0.8	very strong correlation
0.6 ≤ r < 0.8	strong correlation
0.4 ≤ r < 0.6	moderate correlation
r < 0.4	weak correlation

Exact identical data are given if all data pairs are lying on the bisector ($r = 1.0$, $a_1 = 1$, $SD_{diff} = 0$).
The hierarchical evaluation starts with the correlation coefficient. The first necessary condition for good tracking accuracy is a very strong correlation between the markerless and marker-based tracking date.

Table 2
Thresholds of a_1 and SD_{diff} for good tracking accuracy.

a_1	SD_{diff}	
	SegCOG/JC	JAng
[0.9; 1.1]	50 mm	10°

For all kinematical parameters meeting this requirement, a_1 and SD_{diff} were checked. The thresholds of these two statistical parameters, shown in table 2, are based on errors due to marker-based tracking (soft tissue artifact, marker misplacement, etc.) (Fantozzi et al.; Leardini et al., 2005). Thus, one can conclude that good tracking accuracy of markerless tracking compared to marker-based tracking is given if r ≥ .8 and SDdiff as well as a_1 are smaller than the mentioned thresholds presented in table 2.

RESULTS: All movements show a strong correlation (r = 1.0) for the joint center locations as well as for the segment center of gravity locations with a SD_{diff} = 27mm for the SegCOG and SD_{diff} = 29mm for the JC overall movements.
Joint angles, on the other side, require a closer look. The results show that the more complex and faster the movements are, the larger are the differences between marker-based and markerless tracking. Assuming that the marker-based tracking detects the real segment orientations, ignoring the known problems, markerless tracking is less accurate in this situations. The overall results for specific joint movements as well as of complex movements give a very strong correlation for joint angles of the all joint angles in sagittal plane except the elbow joint. Furthermore, adduction-abduction of the hip and the shoulder show very strong correlation. For complex movements, a moderate correlation occurs for joint angles in the frontal and transversal plane. The tennis strokes show smaller correlation coefficients for all joints in the transversal and frontal plane. In sagittal plane, the statistical analysis shows very strong correlation of ankle, knee and shoulder joint angles for all strokes. The two-handed backhand shows a decrease of the correlation coefficient for flexion-extension in the elbow joint and the serve in the hip joint.
Only the knee flexion/extension of both body side was tracked accurate over all tennis strokes (left: r = .95, a1 = 1.05, SD_{diff} = 5.7°, right: r = .95, a1 = 1.02, SD_{diff} = 5.5°).

DISCUSSION: The results reveal that silhouette-based tracking shows less accurate detection of joint angles, especially out of the sagittal plane. A closer look at the segment coordinate systems, which form the basis for joint angle calculation, reveals that it is mainly limited in recognizing the segment rotations around the segment's longitudinal axis. Reason is the model approach for upper and lower extremity segments: they are modeled as more or less cylindrical rigid bodies, resulting in a homogeneous surface without any striking points for better identification of the segment's orientation. This error in orientation identification occurs when the silhouette appearance barely changes during segment rotation. For example, if the shoulder is strongly rotated, the elbow performs a hyperextension instead of a flexion. Another source of error, independent of the tracking method, is the slightly different human model used in the different software. For that reason, joint movements of the trunk are excluded from this survey because the joint centers are placed on different spots within the markerless and marker-based model. In a further investigation, the utilization of hybrid tracking methods should be evaluated. Additional information based on marker or inertial measurement units can stabilize the segment rotations and, thus, improve the output of joint angles accuracy with regard to the three body planes.

CONCLUSION: The study shows that all aspects of joint center and segment center of gravity positions, and thus, their velocity can be accurately measured with silhouette-based tracking. Based on that, 3-point-angles for each joint can be calculated accurate as well. Although there are minor drawbacks of accuracy in comparison to marker-based tracking, it is sufficient to analyze kinematics in training or competition with a good trade-off between practicality (less time, faster in data processing) and accuracy. For applications with a higher demand for accuracy of joint angle data, however, segment rotations should be stabilized by additional orientation information (e.g. based on marker of inertial measurement units).

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