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Evaluation of joint angle accuracy using markerless silhouette-based tracking and hybrid tracking against traditional marker tracking

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Abstract

Markerless tracking is seen as a potential method to make movement analysis quicker, simpler and easier to conduct. Since this technology is still new for application in the fields of medicine and sports, markerless systems have to be evaluated for a sufficient accuracy. The aim of this study is to assess the accuracy of the new silhouette-based tracking software Simi Shape. Both possible applications, markerless tracking and hybrid tracking, which means that some additional markers are used to support the silhouette-based tracking, are tested. Different movements are recorded, specific joint movements as well as complex sports movements. Joint angles of hip, knee, ankle, shoulder and elbow joints are compared to traditional marker-based tracked data by means of the correlation coefficient and the standard deviation of angle difference. Markerless tracking problems are pointed out and hybrid tracking solutions are presented. Problems especially occur for joint rotations for which the silhouettes of the body segments barely change. The results show a very accurate markerless tracking of knee and shoulder movements in the sagittal plane. Also ankle movements in this plane provide good markerless results. For all other movements, very precise tracking results are achieved using hybrid tracking.

The results of this study show that markerless and hybrid tracking provide very accurate joint angle data so that this technology is applicable in all fields of motion analysis.

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List of abbreviations

C7	7th cervical vertebra
fps	frames per second
ICP	iterative closest point
ipf	iterations per frame
ISB	International Society of Biomechanics
lat.	lateral
med.	medial
mid spina	mid spina iliaca posterior superior
MV	mean value
r	correlation coefficient
RMSD	root mean square deviation
SD	standard deviation
Spina left/right	spina iliaca anterior superior left/right
Th8	8th thoracic vertebra

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1 Introduction

1.1 Fields of application and methods of motion analysis

The analysis of human motions is a highly relevant topic in many fields of application. For example, for medical purposes, gait analyses are conducted to detect reasons for movement disorders and to help finding appropriate therapy methods or medical solutions, e.g. by prosthetic fitting. Torburn et al. (1990)[1], for instance, examined different foot prostheses by assessing data obtained during gait analyses. Also in sports, the visualization of movements is an important approach to spot technical deficits and potentials for movement optimization to improve individual sports performances. For example, Tanabe and Ito (2007)[2] analyzed the contribution of upper limb joint movements to the racket velocity during tennis serving. Not only improving performance but also preventing injuries by avoiding inappropriate physical strain is an important topic. Therefore, Ford et al. (2003)[3] examined valgus knee motions during landings in basketball to investigate in reasons for and training methods to prevent knee ligament injuries. For both medical and sports applications instrumental methods are used to gain objective data. A commonly used procedure to capture quantitative movement data is the use of cameras that capture markers which are attached to the analyzed subject. The two main applications on the market differ in the type of cameras: First, there is the possibility to work image-based, which means that synchronized industrial cameras record the motion and by means of image processing algorithms the markers are tracked and 3D coordinates can be calculated. Simi Reality Motion Systems GmbH[4] is a company that develops products for this kind of motion analysis. The other possibility is to use infrared cameras. Retroreflective markers reflect infrared light to cameras and thereby 3D coordinates of markers are calculated. Vicon[5] is a leading company in this field. Both technologies have in common that they use markers that are tracked to gain kinematic movement data. A new technology of motion capture that is developed by Simi is a method that only image-based systems can offer: the possibility of silhouette-based tracking. This

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[1] Torburn, L., Perry, J., Ayyappa, E. and Shanfield, S. L. (1990). Below-knee amputee gait with dynamic elastic response prosthetic feet: A pilot study. Journal of Rehabilitation Research and Development 27(4), pp. 369-384.

[2] Tanabe, S. and Ito, A. (2007). A three-dimensional analysis of the contributions of upper limb joint movements to horizontal racket head velocity at ball impact during tennis serving. Sports Biomechanics 6(3), pp. 418-433.

[3] Ford, K. R., Myer, G. D. and Hewett, T. W. (2003). Valgus Knee Motion during Landing in High School Female and Male Basketball Players. Medicine and Science in Sports and Exercise 35(10), pp. 1745-1750.

[4] Simi Reality Motion Systems GmbH. 2015.

[5] Vicon. 2015.

technology is able to track human motions markerless or as a hybrid variant, which means that some markers support the silhouette-based tracking.

1.2 Requirements of a motion tracking system

There are several aspects that are important considering obtaining data of motion analyses. First of all, the data have to meet a certain degree of accuracy, which is usually dependent of the analysis purpose. For example, scientific works as well as medical and biomechanical applications often require precise data, whereas motion analysis data used for character animation in the film and game industry mostly do not have to meet high accuracy. The second crucial factor is the time that is needed to acquire data. This aspect is closely related to the complexity and accuracy of data, as complex analyses in scientific contexts usually require much time for gaining and analyzing data. On the other hand, in practically orientated applications, e.g. in the clinical field, often several movement analyses have to be conducted per day and therefore, only a short time for each analysis is available. Thirdly, data have to be sufficiently reliable and objective. That means measurements of the exactly same movement have to provide acceptable consistent results conducted on different days or by different examiners. Furthermore, the captured subjects should be as free as possible in their movement executions and not be disturbed by external factors.

1.2.1 Marker-based tracking: Advantages, disadvantages and studies about accuracy

Marker-based tracking is the standard technology of motion capture nowadays. However, there are advantages but also disadvantages of this technology.
Markers can be tracked with a very high accuracy. Tests with the Simi Motion 3D system show a mean failure of < 0.1mm.[6] Furthermore, through attaching at least three markers to each body segment, movements of all segments in all planes can be represented unambiguously. However, there are some problems and disadvantages that occur for marker-based tracking. First, the exact placement of markers is difficult to realize. Although there are exact predefined spots where the markers have to be attached, it is impossible to place them on the exactly same spots for different measurements conducted by the same or by different examiners. Also, errors due to skin and therefore marker movements related to the underlying bones have to be considered.[7] Growney et al.

[6] Bader, J. (2011). Validation of a dynamic calibration method for video supported movement analysis. Unpublished master thesis. Technische Universität München.

[7] Benoit, D. L., Ramsey, D. K., Lamontagne, M., Xu, L., Wretenberg, P. and Renström, P. (2005). Effect of skin movement artifact on knee kinematics during gait and cutting motions measured in vivo. Gait and Posture, 24(2), pp. 152-164. doi:10.1016/j.gaitpost.2005.04.012.

(1996)[8] examined the within-day and between-day reproducibility of lower extremities kinematic and kinetic data. One examiner placed 15 markers on the lower extremities. Gait movements of five subjects were analyzed on three separate test days with three trials each day. Hip, knee and ankle angles were calculated and compared using the coefficient of multiple correlation. Results show a good between-day correlation for sagittal movements of all joints (correlation coefficient (r) $\geq$ 0.95). Out-of-sagittal plane movements show worse correlations, especially in ankle and knee joints ($0.41 \leq r \leq 0.80$). Within-day results report a better repeatability for all joints ($0.77 \leq r \leq 1.00$). Growney et al. found the main reason for the problematic between-day repeatability in differences in marker re-application and movements of the skin-attached markers relative to the underlying bones. Thereby, differences in segment coordinate system axes occur. A less repeatability of out-of-sagittal plane movements is explained by rotations represented as Euler angles. A rotation around a slightly incorrectly defined x-axis causes small errors in flexion/extension angles. However, accumulated errors for rotations around previously incorrect rotated y- and z-axes lead to bigger errors in these joint movements. Furthermore, Growney et al. consider the small ranges of motion performed by out-of-sagittal plane movements compared to sagittal movements as a reason for worse correlations, as small movements compromise the signal-to-noise ratio. Tsushima et al. (2003)[9] tested the test-retest (markers were attached by the same examiner on two different days) and the inter-tester (two different testers attached the markers) reliability attaching 15 markers to the lower extremities in accordance with the VICON Clinical Manager model. Joint angles of lower extremities were calculated and compared by means of the coefficient of multiple correlation. Angles of sagittal movements as well as hip abduction/adduction movements show a high correlation for both test-retest and inter-tester results ($r \geq 0.96$). Worse correlations are reached for all movements in the transversal plane as well as for knee movements in the frontal plane ($0.73 \leq r \leq 0.89$) for test-retest and inter-tester comparison. Another factor that causes difficulties in comparing results of marker-based motion analyses is the use of several protocols for marker placement and biomechanical human models. As a study of Ferrari et al. (2007)[10] shows, for some joint movements there are significant differences in results between different protocols. In the study, markers according to five different worldwide representative protocols were attached to test persons by experienced examiners. Calculated kinematic and kinetic data of trunk, pelvis and lower limbs were compared. The

[8] Growney, E., Meglan, D., Johnson, M., Cahalan, T. and An, K.-N. (1996). Repeated measures of adult normal walking using a video tracking system. Gait and Posture 6, pp. 147-162.

[9] Tsushima, H., Morris, M. E. and McGinley, J. (2003). Test-Retest Reliability and Inter-Tester Reliability of Kinematic Data from a Three-Dimensional Gait Analysis System. Journal of the Japanese Physical Therapy Association, 6(1), pp. 9-17. doi: 10.1298/jjpta.6.9.

[10] Ferrari, A., Benedetti, M. G., Pavan, E., Frigo, C.,Bettinelli, D., Rabuffetti, M., Crenna, P. and Leardini, A. (2008). Quantitive comparison of five current protocols in gait analysis. Gait & Posture 28, pp. 207–216. doi: 10.1016/j.gaitpost.2007.11.009.

results show a high accordance in all joint flexion/extension movements but big differences especially in knee and ankle out-of-sagittal plane and hip transversal plane rotations. One of the protocols even presents an angle range of 35° for knee abduction/adduction movements of a test person with a knee prosthesis that completely prevents these movements.

Table 1 shows an overview of the results that were previously presented. Informations about the used motion analysis systems and camera setups, marker placements, analyzed movements, data that were compared and statistical values that were calculated are stated as they are described in the studies. Also, the results are presented, categorized in sagittal, frontal and transversal plane movements.

Table 1: Overview of results of studies comparing marker-based tracking. Mean values over all analyzed movements, analyzed subjects, body sides and protocols of each study are presented.

Study	System & camera setup	Marker placement	Movement	Comparison	Statistcal value	Results								
						sagittal plane			frontal plane			transversal plane		
						hip	knee	ankle	hip	knee	ankle	hip	knee	ankle
Growney et al.	Expert Vision™, 4 cameras	21 markers, 15 on lower body	gait	within-day	coefficient of multiple correlation	1.00	1.00	0.98	0.98	0.93	0.80	0.95	0.89	0.82
				between-day		0.96	1.00	0.97	0.90	0.59	0.64	0.66	0.48	0.49
Tsushima et al.	Vicon, 4 cameras	model: VCM, 15 markers	gait	between-day	coefficient of multiple correlation	0.99	0.99	0.98	0.97	0.79	-	0.83	0.81	0.82
				inter-tester		0.98	0.99	0.97	0.96	0.78	-	0.80	0.76	0.77
Ferrari et al.	Vicon, 8 cameras	protocols: T3Dg, PiG, SAFLo, CAST, LAMB, total: 60 markers	gait	between protocols	correlation coefficient (Pearson)	1.00	1.00	0.98	0.97	0.26	0.49	0.30	0.52	0.76

All studies show good correlations in sagittal plane angles ($r \geq 0.96$) and hip abduction/adduction movements ($r \geq 0.90$). All other out-of-sagittal movements show worse correlations in at least some studies.

Besides the problems of marker- placement and skin artefacts, the time that is needed to place markers is another adverse factor of marker-based motion analysis. A little survey among clinicians and scientists, who work with a marker-based system, was conducted to quantify the time that is needed for marker placement. The participants stated to need on average 18 min (±7 min) for placing 31 (±7) markers.[11] If many analyses are conducted each day, this is a considerable amount of time. Moreover, if markers are lost during the movement, the whole capturing may have to be repeated. It is also possible that captured subjects change their natural way of movement, as they take care of not losing markers. To conclude, even though markers can be tracked very accurately, by using different protocols or committing small marker placement errors, results can be very different and hard to compare. Furthermore, a considerably amount of time is

[11] Detailed results of the survey: see Appendix A, Table 32.

needed to conduct analyses and subjects may be affected in their usual movement behavior.

1.2.2 Markerless tracking: Advantages and studies about accuracy

There are many advantages of markerless tracking compared to marker-based tracking. First, there are no markers that can be placed incorrectly or lead to inaccuracy because of skin artefacts. Second, much time can be saved if no markers have to be attached and captured subjects are free and undisturbed in their movement. However, in order for the markerless approach to become a standard in movement analysis it has to be accurate and reliable. The use of markerless tracking is still new regarding motion analysis in sports or for clinical purposes. There are some studies that recently evaluated the possibilities of markerless tracking. Markerless approaches are already commonly used in the movie and computer game industry for motion and gesture detection and the animation of characters. Choppin and Wheat (2012)[12] evaluated the accuracy of the markerless tracking software Microsoft Kinect against a marker-based motion capture system (Motion Analysis Corporation). The results show mean root mean square errors of 13° for shoulder and 26.3° for elbow movements in sagittal plane. The focus of these systems is not placed on accuracy but on low costs and the use of uncalibrated cameras. Besides, there are some studies that focus on evaluation of markerless tracking in clinical or sports applications, where accuracy has to be much higher. Rosenhahn et al. (2006)[13] analyzed the elbow flexion/extension angles of a silhouette-based tracking approach against a marker-based system (Motion Analysis Corporation) of a subject performing slow arm forward/backward movements as well as push-ups. Results show overall errors of < 2.5° and indicate an applicability of the system for analyzing elbow angles of slow movements. Corazza et al. (2010)[14] compared joint center data of gait movements between a markerless motion capture approach and a marker-based system (Vicon) using a state of the art protocol Point Cluster Technique[15]. Markerless recorded gymnastic flip movements were not compared to marker-based data since 'marker placement and tracking is very challenging for gymnastics movements' [16]. Results show joint center deviations of 15 mm (± 10 mm) over all analyzed joints (hip, knee, ankle, shoulder, elbow and wrist). Markerless tracking of fast movements of gymnastic flips was only

[12] Choppin, S. and Wheat, J. (2012). Marker-less tracking of human movement using Microsoft Kinect. 30th annual condefence of biomechanics. Melbourne.

[13] Rosenhahn, B., Brox, T., Kersting, U. G., Smith, A. W., Gurney, J. K. and Klette, R. (2006). A system for marker-less motion capture. Künstliche Intelligenz (KI), No. 1, pp. 45-51.

[14] Corazza, S., Mündermann, L., Gambaretto, L., Ferrigno, G. and Andriacchi, T. P. (2010). Markerless Motion Capture through Visual Hull, Articulated ICP and Subject Specific Model Generation. International Journal of Computer Vision 87(1), pp. 156-169.

[15] Andriacchi, T. P., Alexander, E. J., Toney, M. K., Dyrby, C. O. and Sum, J. A. (1998). A point cluster method for in vivo motion analysis: applied to a study of knee kinematics. Journal of Biomechanical Engineering, 120, pp. 743–749.

[16] Corazza et al. (2010), p. 158.

evaluated visually and assessed as robust and accurate. Joint centers of shoulder, elbow and wrist were also evaluated by Ceseracciu et al. (2011)[17]. They used a modified version for underwater tracking of the markerless tracking approach of Corazza et al. (2010)[14] and compared markerless joint center data of frontal crawl swimming to data obtained with a marker-based motion capture software (Simi Motion) by calculating root mean square deviations (RMSD). Especially elbow and shoulder joint centers show large deviations (> 90 mm) in longitudinal direction. Oberländer and Brüggemann (2011)[18] assessed the accuracy of markerless tracking by comparing markerless data obtained with the software BioStage to marker-based data obtained with a Vicon system. Hip, knee and ankle joint angle data in sagittal plane were analyzed by means of correlation coefficient and RMSD. Results are good in all joints ($r \geq 0.89$, RMSD ≤ 3.4°). Ceseracciu et al. (2014)[19] compared joint angle data of hip, knee (only in sagittal plane) and ankle gained by a markerless approach to marker-based data obtained with an optoelectronic motion capture system (BTS) using a modified version of IORgait protocol. Among others, standard deviations (SD) of RMSD between marker-based and markerless data were calculated. The smallest deviations are found for ankle and knee movements in the sagittal plane and hip movements in the frontal plane (SD RMSD ≤ 2.5°). The worst results occur for hip movements in the transversal plane. Mündermann et al. (2006)[20] evaluated markerless knee joint angle data in sagittal and frontal planes against marker-based data obtained with an optoelectronic system (Qualisys) by calculating the average deviation of joint angle deviations. Results show small values (< 2.5°) for both planes. The same authors[21] also used a virtual environment to compare markerless tracking data to a virtual character with known kinematics using Poser® software and 16 cameras. Results show RMS errors of ≤ 4.4° for hip, knee and shoulder movements in sagittal and frontal planes, errors for ankle movements are a bit higher (9.0° resp. 5.9°).

[17] Ceseracciu, E., Sawacha, Z., Fantozzi, S., Cortesi, M., Gatta, G., Corazza, S. and Cobelli, C. (2011). Markerless analysis of frontal crawl swimming. Journal of Biomechanics 44, pp. 2236-2242.

[18] Oberländer, K. D. and Brüggemann, G.-P. (2011). Validation of a real-time markerless tracking system for clinical gait analysis -ad hoc results-. American Society of Biomechanics.

[19] Ceseracciu, E., Sawacha, Z. and Cobelli, C. (2014). Comparison of Markerless and Marker-Based Motion Capture Technologies through Simultaneous Data Collection during Gait: Proof of Concept. PLoS ONE 9(3): e87640. doi:10.1371/journal.pone.0087640.

[20] Mündermann, L., Corazza, S. and Andriacchi, T. P. (2006). The evalution of methods for the capture of human movement leading to markerless motion capture for biomechanical applications. Journal of NeuroEngineering and Rehabilitation, 3:6. doi: 10.1186/1743-0003-3-6.

[21] Corazza, S., Mündermann, L., Chaudhari, A. M., Demattio, T., Cobelli, C. and Andriacchi, T. P. (2006). A Markerless Motion Capture System to Study Musculoskeletal Biomechanics: Visual Hull and Simulated Annealing Approach. Annals of Biomechanical Engineering, Vol. 34, No. 6, pp. 1019-1029. doi: 10.1007/s10439-006-9122-8.

Table 2 and Table 3 present an overview of those of the previously presented studies that compare joint angles.[22] In Table 2, information about used systems, camera setups and analyzed movements are given.

Table 2: Overview of studies comparing markerless to marker-based tracking resp. tracking in a virtual environment. Information about the used system, camera setup and analyzed movement of each study are presented.

Number	Study	System & camera setup			Movement
		markerless	system for comparison	cameras	
1	Choppin & Wheat	Microsoft Kinect	Motion Analysis Corporation	?	reaching, throw
2	Rosenhahn et al.	own approach	Motion Analysis Corporation	8	slow arm movements, push-ups
3	Oberländer & Brüggemann	BioStage	Vicon	12	gait
4	Ceseracciu et al.	own approach	BTS SMART-D	8	gait
5	Mündermann et al.	own approach	Qualisys	8	gait
6	Corazza et al.	own approach	virtual environment, Poser software	16	gait

The related statistical values and results are shown in Table 3. In all studies, angle deviations between markerless and marker-based tracked angle data were calculated, nevertheless with slightly different statistical methods. In some studies, the precise calculation is not stated so that an exact comparability of the values is questionable. However, all results are about the same dimension so that a good comparability is likely. The significantly higher values that are found in study 1 are due to an inaccurate markerless tracking system as the authors state.

Table 3: Continuation of Table 2. Results of the studies (mean values over all movements, analyzed subjects and body sides of each study) are presented.

Number	Statistcal value	Results											
		sagittal plane					frontal plane				transversal plane		
		hip	knee	ankle	shoulder	elbow	hip	knee	ankle	shoulder	hip	knee	ankle
1	root mean square error [°]	-	-	-	13.0	26.3	-	-	-	-	-	-	-
2	overall error [°]	-	-	-	-	2.0	-	-	-	-	-	-	-
3	root mean square deviation [°]	1.9	3.4	2.5	-	-	-	-	-	-	-	-	-
4	SD of root mean square distance [°]	8.5	2.5	1.8	-	-	2.3	-	3.6	-	9.3	-	7.0
5	average deviation of the deviation of joint angles [°]	-	2.3	-	-	-	-	1.6	-	-	-	-	-
6	mean absolute errors [°]	3.6	4.2	9.0	4.4	-	2.0	3.1	5.9	4.0	-	-	-

The results show that most available studies do not investigate in transversal plane joint

[22] For a better overview, the tables are split. Their content is related according to the numeration.

movements. Also upper body joint angles are often not considered in the analyses. The Microsoft Kinect system (study number 1) is not developed to provide highly accurate data and to be used in sports and medical applications. Most of the other studies show small angle deviations in most joint movements (< 5°). Higher values only occur for movements in the transversal plane (9.3° for the hip resp. 7.0° for the ankle) and hip movements in the sagittal plane (8.5°) in the study of Ceseracciu et al. and for ankle movements in the study of Corazza et al. (9° for sagittal and 5.9° for frontal plane movements).

Regarding the results of studies about the accuracy of markerless tracking, the potential of this technology is obvious. However, there are no studies that analyzed all relevant joint angles for different, slow and fast, movements yet. Many studies focus solely on a few joints and often only on movements in the sagittal plane. Furthermore, most studies are confined to slow motions such as gait movements. Especially for sports applications where fast movements are very common, there are no markerless tracking approaches tested sufficiently for all relevant joints yet.

1.3 Motivation and aim of the thesis

The current state of research shows that marker-based motion capture has some disadvantages that can be avoided by using markerless tracking. Nevertheless, there are no studies about evaluating the accuracy of markerless tracking for all major joints and for different, slow as well as fast, movements yet. Studies that are available often show inaccuracy of markerless tracking, especially for out-of-sagittal plane movements. Therefore, markerless tracking so far is only widely used for applications in the film and game industry, where accuracy is less important. For medical and sports applications, a higher accuracy is demanded. The aim of this thesis is to evaluate a new commercial silhouette-based motion tracking software (Simi Shape 3D) against a traditional marker-based software (Simi Motion 3D) regarding joint angle accuracy for all major joints and different movements. Moreover, the application of hybrid tracking (a combination of silhouette and marker tracking) is supposed to be analyzed as a possibility to be used for joint rotations for which no sufficient accuracy can be reached markerless.

2 Theoretical background

This chapter will first present the technical setup that is used to record movements, second, the different possibilities of motion tracking are explained and finally, anatomical and biomechanical foundations of human joints and movements are given.

2.1 Technical equipment, system setup and calibration

For the study, several recordings of movements were required. All these recordings were made in the Simi laboratory. The laboratory is equipped with eight Basler scA640-120gc cameras with a resolution of 659x494 pixels. Fujinon 3.8-13mm DV3.4x3.8SA-SA1 lenses and LED ringlights are mounted on the cameras (Figure 1).

Figure 1: Lens and ringlight mounted on the camera.[23]

Each camera is connected to the computer by an ethernet cable to enable data transfer. Furthermore, the cameras are connected to an I/O box by trigger cables to ensure a synchronization of the videos and a power supply of the cameras. The I/O box is therefore connected to the computer and to an external power supply.[24] Another essential part of the system are retroreflective markers. These markers that are attached to the captured subject are illuminated by the ringlights and reflect the light so that they are visible as white spots in the videos.

Before movements for analysis are recorded, the system has to be calibrated. This is realized with a T-wand and an L-frame is used to define the global coordinate system (Figure 2). The positive y-axis is determined in direction of movement resp. view of the analyzed subject. The positive x-axis points to the right perpendicular to the y-axis. The z-axis is defined as perpendicular to the x- and y-axes applying a right-handed coordi-

[23] Simi Reality Motion Systems GmbH. September 11, 2015. Motion – Benutzerhandbuch - Simi Motion Version 9.1.1 build 354. Unterschleißheim, p. 50.

[24] ibid., pp. 49-51.

nate system. For the dynamic calibration, the T-wand with a known distance between the attached markers is moved within the recording area. The markers are automatically tracked and assigned in Simi Motion and the known distances between them are given to the system to calculate calibration data.[25]

Figure 2: T-wand for calibration and L-frame for defining a global coordinate system.[26]

2.2 Methods of motion tracking

There are different methods of motion tracking and therefore different software products that are developed by Simi. The two products that are used in this study are Simi Motion 3D (the latest version 9.1.1) and Simi Shape 3D (the latest version 2.1.1). In Simi Motion it is possible to get kinematic movement data by tracking markers. Simi Shape is an upgrade of Simi Motion. With this software it is possible to conduct markerless or hybrid motion tracking. In the following, these software applications and the methods of marker-based, markerless and hybrid movement analysis are explained.

2.2.1 Marker-based tracking in Simi Motion

The basic principle of motion tracking in Simi Motion is the use of retroreflective markers that are attached to body segments and joints. The markers are tracked in each camera, 3D data are computed if a marker is visible in at least two cameras and inverse kinematic data can be calculated. A human model consisting of 16 segments (foot, shank, thigh, upper arm, forearm, hand, head, upper torso, lower torso and pelvis) that are linked by joints is used for calculation. To be able to obtain inverse kinematic data, markers have to be attached to the body according to a predefined marker set. The markers determine the joint locations as well as the center of mass of each segment. They are also used to define local segment coordinate systems which have their origin in the particular center of mass (Figure 3). The joint centers of ankle, knee, elbow and

[25] ibid., pp. 122-126.
[26] ibid., p. 123.

wrist are defined as center of the connection line between the medial and lateral markers of the particular joint.[27] Hip and shoulder joints are calculated in a more complex way according to the works of Bell et al.[28] and De Leva[29].

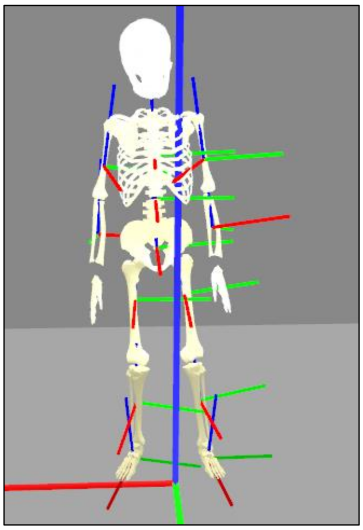

Figure 3: Local segment coordinate systems (red: x-axes, green: y-axes, blue: z-axes).

According to the International Society of Biomechanics (ISB) standard[30,31] and Grood et al.[32], special joint coordinate systems are defined to describe joint rotations. These coordinate systems can be unambiguously converted into segment coordinate systems. Each joint consists of two joint coordinate systems: One of the proximal and one of the distal segment. Joint angles are described as rotations between the two joint coordinate systems. The rotation of the distal segment is calculated in the coordinate system of the proximal segment. Internally, they are given as rotation matrices and are then converted to x, y, z-Cardan angles for output data that can be easily interpreted. The first angle describes a rotation around the x-axis of the distal joint coordination system, followed by rotations around the y- and z-axes of the previously once resp. twice rotated coordi-

[27] ibid., pp. 365-366.

[28] Bell, A. L., Pedersen, D. R. and Brand, R. A. (1990). A comparison of the accuracy of several hip center location prediction methods. Journal of Biomechanics, 23(6), pp. 617 – 621.

[29] De Leva, P. (1996). Joint center longitudinal positions computed from a selected subset of Chandler's data. Journal of Biomechanics, 29(9), pp. 1231–1233.

[30] Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D'Lima, D. D., Cristofolini, L., Witte, H. and Schmid, O. (2002). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion – part I: ankle, hip, and spine. Journal of Biomechanics, 35(4), pp. 543–548.

[31] Wu, G., Vanderhelm, F., Dirkjanveeger, H., Makhsous, M., Vanroy, P., Anglin, C., Nagels, J., Karduna, A., McQuade, K. and Wang, X. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion – Part II: shoulder, elbow, wrist, and hand. Journal of Biomechanics, 38(5), pp. 981–992.

[32] Grood, E. S. and Suntay, W. J. (1983). A joint coordinate system for the clinical description of three-dimensional motions: Application to the knee. Journal of Biomechanical Engineering, 105(2), pp. 136–144.

nate systems.[33]

The two marker sets that are used in this study are a set for the lower extremities and one for the whole body.[34] With these marker sets, inverse kinematic data of the lower extremities or of the whole body can be calculated with the Simi Motion Inverse Kinematics module[35]. Figure 4 depicts the spots where markers have to be attached for both marker sets.

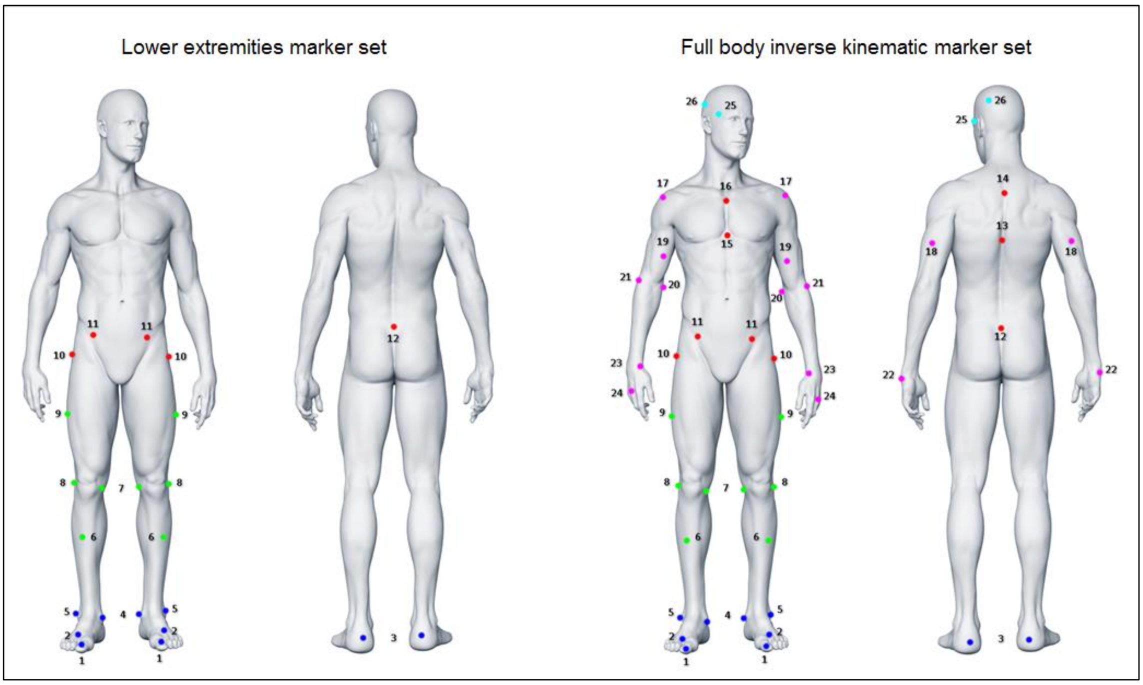

Figure 4: Marker placements according to a marker set for lower extremities (left) and a full body inverse kinematic marker set (right).

Table 4 shows the marker labelling according to the numbers than can be seen in Figure 4.[36]

[33] Simi Reality Motion Systems GmbH. 2015. Motion – Benutzerhandbuch, pp. 370-371, 374.

[34] Hunter, J. and Ferdinands, R. (2002). A three dimensional marker system for motion analysis system software Technical report, specially prepared for Simi Reality Motion Systems.

[35] The Inverse Kinematic module performs the steps that were described before.

[36] Simi Reality Motion Systems GmbH. 2015. Motion – Benutzerhandbuch, pp. 375-379.

Table 4: Marker labels of the lower extremities and full body marker sets.

Number	Marker label	Number	Marker label
1	foot tip left/right	**14**	7th cervical vertebra (C7)
2	forefoot left/right	**15**	processus xiphoideus
3	heel left/right	**16**	sternum
4	malleolus medialis left/right (med. ankle)	**17**	acromion left/right
5	malleolus lateralis left/right (lat. ankle)	**18**	triceps left/right
6	shank left/right	**19**	biceps lateral left/right
7	condylus medialis left/right (med. knee)	**20**	epicondylus medialis left/right (med. elbow)
8	condylus lateralis left/right (lat. knee)	**21**	epicondylus lateralis left/right (lat. elbow)
9	thigh lateral left/right	**22**	articulatio composita medialis left/right (med. wrist)
10	trochanter major left/right	**23**	articulatio composita lateralis left/right (lat. wrist)
11	spina iliaca anterior superior left/right (spina left/right)	**24**	middle finger base joint left/right
12	mid spina iliaca posterior superior (mid spina)	**25**	tempus (temple) left/right
13	8th thoracic vertebra (Th8)	**26**	back of the head left/right

When the markers are attached to the body, first a static trial is recorded. The recorded subject is standing in an upright position with the arms hanging straight besides the body. This pose is used for calculating person-specific data such as the lengths of body segments and the location of joint axes.[27] After the static trial, the dynamic trial that contains the movement that is supposed to be analyzed is captured and markers are automatically tracked in Simi Motion.[37] One initialization frame is needed in that each marker is assigned correctly in at least two cameras. The assignment for the rest of the recording is done automatically using the initialization frame and the implemented marker set.[38] As mistakes in the automatic tracking and assignment can occur (e.g. jumps between markers, markers are not recognized in at least two cameras) there are several methods to check the tracking data. To identify big mistakes or missing markers, a representation of the data as a 3D stick figure can be used.[39] To identify smaller tracking faults, the video images can be overlayed by the calculated 3D data (red crosses) to check accordance with the markers (Figure 5).[40]

[37] ibid., p. 154.
[38] ibid., p. 164.
[39] ibid., pp. 300-301.
[40] ibid., p. 443.

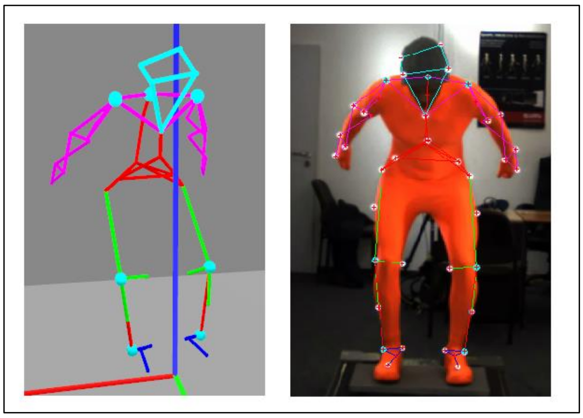

Figure 5: Possibilities to identify tracking problems. 3D Stick figure (left) and video overlay (right).

2.2.2 Silhouette-based markerless tracking in Simi Shape

The software Simi Shape 3D enables motion capture without using markers. The tracking process works on the base of silhouettes into that a human model is fitted.
The camera setup and calibration procedure is the same as for marker-based tracking in Simi Motion. Ringlights are not needed as no reflective markers have to be lighted. For silhouette-based tracking, it is important to have a good contrast between the captured subject and the background. To guarantee this in every situation, the wearing of a colored morphsuit is recommended (Figure 7). However, this is not necessary as long as other clothes provide a good contrast to the background and are close fitting to the body.[41]
The execution of markerless tracking can be divided into three steps: segmentation, model initialization and tracking (compare Figure 6).

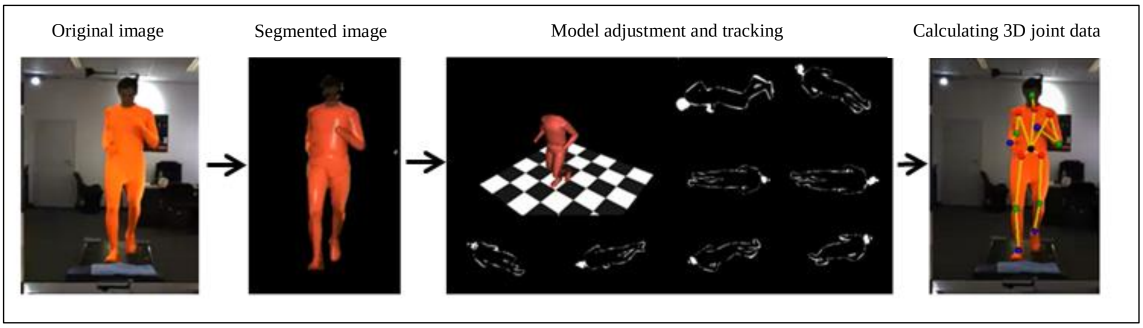

Figure 6: Simi Shape workflow.

The purpose of segmentation is to separate the recorded subject from the background in all camera images. The first step that is conducted to get a segmented image is the so-called background subtraction. Therefore, a recording of the empty room without the

[41] Simi Reality Motion Systems GmbH. April 15, 2015. Shape – User's Manual – Simi Shape Version 2.0.1. Unterschleißheim, p. 29.

subject that is supposed to be analyzed is needed. The surrounding conditions (e.g. concerning equipment and lighting) have to be the same as for the motion video. By subtracting the background and the motion images from each other (every pixel is compared concerning color and intensity and classified either as part of the background or of the analyzed subject), only the silhouette of the subject remains for each camera. Segmentation can be improved by applying information about pixels belonging to the background or foreground from one camera to the others (the so-called space carving). This is especially useful if the background conditions cannot be kept stable in some cameras, e.g. because of changing light conditions.[42] Out of 2D silhouettes from at least two cameras, a 3D silhouette of the subject can be computed. In the next step, model initialization, a mathematical 3D model is fitted into the silhouette. The Shape model consists of 16 segments (pelvis, torso, neck, head, upper arm, forearm, hand, thigh, shank, foot) which are linked by joints.[43] The following joints are part of the model: root joint (3 translational and 3 rotational degrees of freedom), 5th lumbar vertebra, 7th cervical vertebra, shoulder joint, wrist joint, hip joint, ankle joint (all of them with 3 rotational degrees of freedom), skull base, elbow joint and knee joint (all of them with 1 rotational degree of freedom).[44] Joint centers are defined within the model and joint coordinate axes are computed in a static position: The subject is standing upright with the arms close to the body, tiptoes and thumbs are pointing forwards. For joint angle data calculation, the coordinate axes are converted so that they are consistent with joint coordinate axes of marker-based data in Simi Motion.[45] The model can be adjusted to the subject that is performing the movements automatically. During this process, the lengths and widths of the model segments are aligned to the actual segment lengths and widths of the captured subject (scaling and deformation). Furthermore, the pose of the model is fitted to the subject's pose. Automatic pose optimization as well as scaling and deformation can be executed well if an initialization frame is chosen in that the subject is seen in all cameras and with all joints in a slightly bent position. A very suitable pose is the so-called Psi-pose (Figure 7). If needed, the segment dimensions and the joint positions can also be adjusted manually.[46]

[42] ibid., pp. 65-66.
[43] The model is based on the work of 'Dreyfuss, H. and Tilley, A. R. (2002). The Measure of Man and Woman: Human Factors in Design (Architecture). John Wiley and Sons, Inc.' and further developed by Simi Reality Motion Systems GmbH by conducting internal tests with different probands.
[44] Simi Reality Motion Systems GmbH. 2015. Shape – User's Manual, pp. 21-22.
[45] Wehrheim, J. (2015). Personal talk.
[46] Simi Reality Motion Systems GmbH. 2015. Shape – User's Manual, pp. 32-33.

Figure 7: Psi pose for model initialization.[47]

When the model is fitted well, the tracking can be started. For tracking, an iterative closest point (ICP) algorithm is used to adjust the pose of the model to the actual pose of the 3D silhouette for each frame by looking for correspondences between the silhouette and the model.[48] During the tracking, motion data such as joint angles are read from the pose of the model and saved.

2.2.3 Hybrid tracking in Simi Shape

Hybrid tracking is a combination of marker- and silhouette-based tracking that can be executed in Simi Shape. The tracking procedure is the same as for markerless tracking that is explained in the previous chapter. The only difference is that additional markers are implemented and taken into computation to support the silhouette tracking. Therefore, the markers that are supposed to be used have to be tracked in Simi Motion before.[49] Similarly to markerless tracking, 3D joint data can be read from the model for each frame.

2.2.4 Factors that influence the accuracy of marker-based, markerless and hybrid tracking

There are several parameters that influence the accuracy of marker-based, markerless and hybrid tracking (Table 5). For markerless and hybrid tracking, all parameters that can be set in Simi Shape are listed. As only the factors ‘weight for silhouette-correspondences’ and ‘weight for marker-correspondences’ were tested in this study, these parameters are explained in detail. For all other factors, short explanations are presented as they are published in the Simi Shape - User’s Manual. [50]

[47] Simi Reality Motion Systems GmbH. 2015. Shape – User’s Manual, p. 13.
[48] ibid., p. 69.
[49] ibid. pp. 23-24.
[50] ibid., pp. 69-72.

Table 5: Factors that influence the accuracy of marker-based, markerless and hybrid tracking.

<table>
<tr><th>Marker-based</th><th>Markerless</th><th>Hybrid</th></tr>
<tr><td colspan="3">number and positioning of cameras</td></tr>
<tr><td colspan="3">camera resolution</td></tr>
<tr><td colspan="3">calibration quality</td></tr>
<tr><td colspan="3">human model</td></tr>
<tr><td>accuracy of marker placement</td><td colspan="2"></td></tr>
<tr><td>used marker placement protocol</td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2">use Hymo-tracking</td></tr>
<tr><td></td><td colspan="2">use silhouette-correspondences</td></tr>
<tr><td></td><td colspan="2">use inverse silhouette-correspondences</td></tr>
<tr><td></td><td colspan="2">use motion constraints</td></tr>
<tr><td></td><td colspan="2">iterations per frame</td></tr>
<tr><td></td><td colspan="2">minimal size of rendered contours</td></tr>
<tr><td></td><td colspan="2">minimal size of segmented contours</td></tr>
<tr><td></td><td colspan="2">stepwidth for silhouette-corresondences</td></tr>
<tr><td></td><td colspan="2">stepwidth for inverse silhouette-corresondences</td></tr>
<tr><td></td><td colspan="2">direction-tolerance for silhouette-correspondences</td></tr>
<tr><td></td><td colspan="2">maximal distance of silhouette-correspondences</td></tr>
<tr><td></td><td colspan="2">maximal distance of inverse silhouette-correspondences</td></tr>
<tr><td></td><td colspan="2">confidence range for silhouette-correspondences</td></tr>
<tr><td></td><td></td><td>weight for silhouette-correspondences</td></tr>
<tr><td></td><td></td><td>weight for 3D-marker-correspondences</td></tr>
<tr><td></td><td colspan="2">weight for motion constraints</td></tr>
<tr><td></td><td colspan="2">initial augmentation parameter</td></tr>
<tr><td></td><td colspan="2">scaling of augmentation per iteration</td></tr>
</table>

- *Use Hymo-tracking*: ‘This checkbox activates the silhouette-based ICP-tracking algorithm. If deactivated the tracking algorithm of Simi Shape3D ® version 1.0 based on pixel-counting is applied.’
- *Use silhouette-correspondences*: ‘If this option is activated the tracking algorithm scans the contour of the silhouette of the rendered model and tries to find corresponding contour points on the silhouette of the segmented image.’
- *Use inverse silhouette-correspondences*: ‘If this option is activated the tracking algorithm scans the contour of the silhouette of the segmented image and tries to find corresponding contour points on the silhouette of the rendered model.’
- *Use motion-constraints*: ‘All our models are equipped with a set of motion-constraints that prevent them from taking unrealistic poses. Deactivate this option if you want to allow any kind of motion.’

- *Iterations per frame*: 'For every frame the pose of the model is optimized iteratively. Increase the number of iterations to gain accuracy. Decrease the number to gain speed.'
- *Minimal size of rendered contours*: 'Contours of the rendered silhouette consisting of less pixels than specified here are ignored.'
- *Minimal size of segmented contours*: 'Contours of the segmented silhouette consisting of less pixels than specified here are ignored.'
- *Stepwith for silhouette-correspondences*: 'While the rendered contour is scanned for correspondencegeneration this stepwidth is applied.'
- *Stepwidth for inverse silhouette-corresondences*: 'While the segmented contour is scanned for correspondence-generation this stepwidth is applied.'
- *Direction-tolerance for silhouette-correspondences*: 'A correspondence between a rendered and a segmented contour point is only allowed if a certain condition on the normal-directions of the silhouettes at the respective points is satisfied. This direction-tolerance ranges from 0 (normal directions must be identical) to 4 (no condition). Increase this number to get more correspondences. Decrease this number to get better correspondences.'
- *Maximal distance of silhouette-correspondences*: 'A correspondence from a rendered contour point is only allowed to segmented contour points within this radius.'
- *Maximal distance of inverse silhouette-correspondences*: 'A correspondence from a segmented countour point is only allowed to rendered contour points within this radius.'
- *Confidence range for silhouette-correspondences*: 'Correspondences between contour points with a distance exceeding this number are weighted down.'
- *Weight for motion constraints*: 'An additional weight factor that is applied to all motion-constraints.'
- *Initial augmentation parameter*: 'This is the exponent of the initial augmentation parameter of the Levenberg-Marquardt algorithm that is applied in every frame to optimize the model pose.'
- *Scaling of augmentation per iteration*: 'The Levenberg-Marquardt algorithm starts optimization in every frame with the above initial value and then scales the augmentation parameter after each iteration with this factor.'

Weight for silhouette- and 3D-marker-correspondences

Important tracking settings for hybrid tracking are the parameters 'weight for silhouette-correspondences' and 'weight for 3D-marker-correspondences'. These parameters determine if the model is taking its position rather based on marker data or on silhouette-correspondences.[51] If the weight for silhouette-correspondences is set too small, segments that are not unambiguously defined by three markers may lose correspondence with the silhouette. This rarely, but sometimes, happens if equally weighted silhouette- and marker-correspondences are used and can lead to a falling apart of the model (Figure 8). Tracking settings with a 20-fold higher weight for silhouette-correspondences than for marker-correspondences have proved to allow stable trackings.

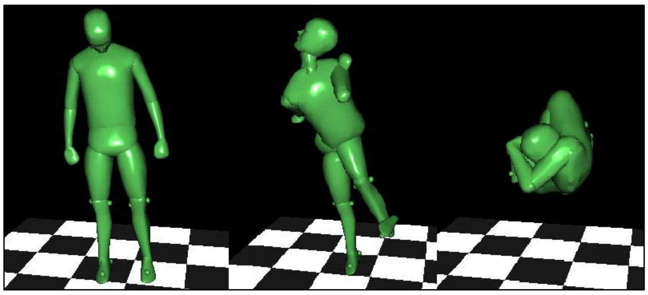

Figure 8: Falling apart of the Shape model using equally weighted marker- and silhouette-correspondences.

If joint rotations for that both segment's rotations are clearly defined in the regarded plane by using markers (e.g. spina right and left as well as med. and lat. knee markers for hip rotation movements) are supposed to be tracked, a tracking with equally weighted marker- and silhouette-correspondences is likely to provide good tracking results. The reason is that for higher marker-correspondences compared to silhouette-correspondences, it is less possible for a model segment to perform slightly incorrect movements within the silhouette.

2.3 Anatomical and biomechanical foundations of human joints and joint movements

In this section, anatomical and biomechanical foundations concerning human movements, and especially of the joints that are analyzed in this study, are presented.

2.3.1 Body planes and axes

In order to be able to describe movements, different body planes in which movements take place and axes around which movements occur are classified (Figure 9). The three main axes are:

- Sagittal axis: Running from the back to the front of the body.
- Longitudinal axis: Running from the top to the bottom of the body.

[51] ibid., p. 71.

- Transversal axis: Running from the left to the right half of the body.

According to the axes, body planes are defined as:

- Sagittal plane: Defined by the longitudinal and sagittal axes. Divides the body into a symmetrical right and left part.
- Frontal plane: Defined by the longitudinal and transversal axes. Divides the body into a front and a back half.
- Transversal plane: Defined by the transversal and sagittal axes. Divides the body into a top and a bottom half.[52]

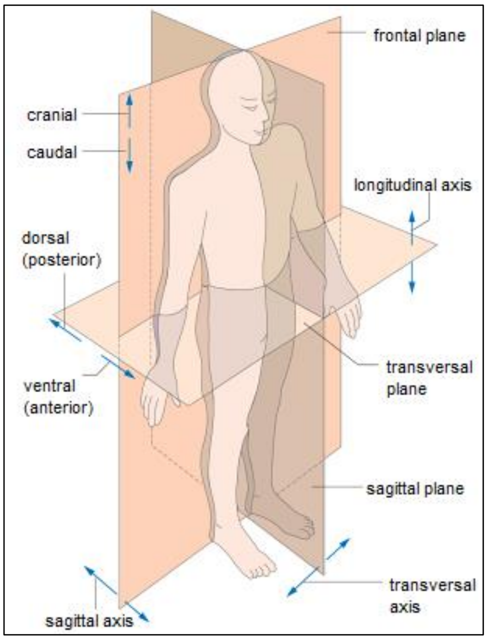

Figure 9: Body planes and axes.[52]

2.3.2 Structure of human joints and possibilities of movement

A joint is a flexible connection between two or more bones and comprises the joint head of one bone that lies in the joint socket of the other bone. In order to prevent friction between the two bones, these are covered with articular cartilage. Furthermore, there is a liquid ('synovial fluid') located in the joint space between the two bones that, on the one hand, ensures a smooth sliding of the bones against each other and, on the other hand, supplies the cartilage with nutrients. The synovial fluid is discharged from the joint capsule, which encloses the entire joint. The joints are stabilized by ligaments that are also responsible for the possibilities of movement in each joint. To enable movement, muscles are connected to the bones by tendons.[53] One differentiates between vari-

[52] Bommas-Ebert, U., Teubner, P. and Voß, R. (2001). Kurzlehrbuch Anatomie und Embryologie, 3. Auflage. Stuttgart: Georg Thieme Verlag, p. 3.
[53] Dimon Jr, T. (2001). Anatomy of the moving body. A basic course in bones, muscles and joints, Second edition. Berkeley: North Atlantic Books, pp. 13-15.

ous kinds of joints, which are characterized by their shape and their degrees of freedom (Figure 10): Hinge and pivot joints are monaxial joints that only have one degree of freedom and thus allow only movements around one axis. Saddle, condyloid and plantar joints are biaxial joints with two degrees of freedom and ball-and-socket joints are classified as triaxial joints that consequently allow movements around three axes.[54]

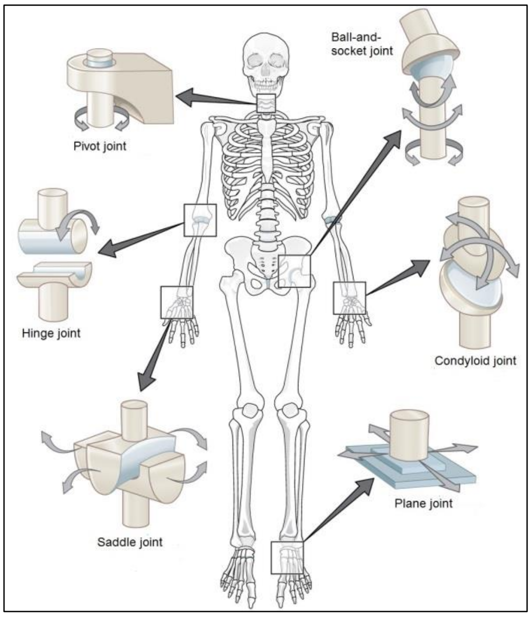

Figure 10: Types of human joints.[55]

In this work, the hip, knee, ankle, shoulder and elbow joints are examined. Therefore, these joints are described below, focussing especially on the possibilities of motion of each joint.[56]

Hip joint

The hip joint is classified as a ball-and-socket joint. Movements around three axes are possible. First, flexion/extension movements around the transversal axis can be performed. A hip flexion is defined as a movement of the front side of the thigh towards the body; a hip extension accordingly as a movement in the opposite direction. The range of motion is strongly dependent of the knee position and of the question if the motion is performed actively or passively (e.g. with help of the arms). With a stretched

[54] Tortora, G. J. and Derrickson, B. (2009). Principles of anatomy and physiology, 12th edition. John Wiley and Sons, Inc., pp. 276-277.
[55] Anna's Dance Term 1 Blog Yr 11. (2015). Synovial Joints.
[56] It hast to be noted that the in the following stated ranges of motion are values of the average human. The possibilities of motion are dependent of the anatomy of the joint as well as of the ligaments that surround the joint. Especially the ligaments can be stretched by training and therefore often allow a higher mobility in the joint.

knee, a hip flexion with an angle of about 90° is possible, with a bent knee the angle increases to 120° or even more. For passive flexion in the hip joint, amplitudes of more than 140° can be reached. An active extension with a stretched knee is executable up to about 20°, with a bent knee up to approx. 10°. Passively, for example by pulling the leg backwards with the arms, an angle of about 30° can be reached. Another axis around which movements in the hip joint can be performed is the sagittal axis. A movement of the leg away from the body is called abduction and can be actively executed up to an angle of about 45°. Passively and with specific training, an abduction of 90° can be reached. A movement in the opposite direction (the leg is moved towards the body) is defined as adduction. Starting in neutral position (standing upright, the legs hip width apart and the arms hanging relaxed next to the body with the thumbs pointing forward)[57], an adduction can only be performed together with a hip flexion or extension or with a simultaneously abduction of the other leg. Adduction angles up to 30° can be achieved. The third kind of movement that can be performed in the hip joint is a rotation around the longitudinal axis of the leg. Conducting an internal rotation, the leg is rotated in direction of the big toe, for an external rotation in the opposite direction. Internal rotations are possible up to an angle of approx. 40°, external rotations up to about 60°.[58]

Knee joint

The knee joint is classified as a modified hinge joint.[59] Motions can be performed in sagittal direction around the transversal axis. They are described as flexion (the back side of the shank is led towards the back side of the thigh) and extension (the back side of the shank moves away from the back side of the thigh). Starting in neutral position, an active extension is usually not possible. Passively, a hyperextension of about 5-10° can be reached. An active knee flexion is executable up to 140° if the hip joint is bent. With an unbent hip joint, a maximal knee flexion of approx. 120° is possible. A passive flexion of the knee is executable up to an angle of about 160°. Furthermore, if the knee is bent, a rotational movement of the shank around its longitudinal axis is possible. An internal rotation (out of neutral position the toes move towards the sagittal body plane if the ankle does not rotate) is feasible up to an angle of approx. 30°, an external rotation (rotation in the other direction) is possible up to about 40°. The possibility of the knee to rotate gets higher with a stronger bent knee. If the knee is completely stretched, no rotation is possible. Medial and lateral collateral ligaments have the function to prevent ab-

[57] DocCheck Flexikon – The cooperative medical dictionary. (2015). Neutral Position.
[58] Kapandji, I. A. (2009). Funktionelle Anatomie der Gelenke. Band 2: Untere Extremität, Stuttgart: Georg Thieme Verlag, pp. 2-12.
[59] Tortora, G. J. and Derrickson, B., p. 290.

duction/adduction movements in the knee joint. Nevertheless, small movements are also possible in the frontal plane.[60]

Ankle joint

The ankle joint is made up of two main joints: the upper and the lower ankle joint. In the upper ankle joint, which is a hinge joint, flexion movements in sagittal direction around an axis that goes through the lat. and med. ankle can be performed. A movement of the foot in direction of the shank is called dorsal flexion, a movement in the other direction a plantar flexion. The amplitude of a dorsal flexion is maximal 20-30°, a plantar flexion is possible up to an angle of approx. 50°.[61] Further movements that can be performed by the foot mainly take place in the lower ankle joint. First, a motion around the longitudinal axis of the shank, which is defined as abduction and adduction, is possible. Performing an adduction, the toes move towards the sagittal body plane, an abduction is the movement in the opposite direction. Ab- and adduction movements can be performed up to angles of 35-45°. Another kind of movement that is mainly performed in the lower ankle joint takes places around the longitudinal axis of the foot. This movement is called pronation (the bottom of the foot points outward) or supination (the bottom of the foot points inward). The maximal amplitude of a supination is about 50°, a pronation is possible up to 30°. Pronation and supination do not occur in pure form. A pronation is always accompanied by a dorsal flexion and an abduction movement. This combined movement is called eversion. Similarly, a supination always occurs together with a plantar flexion and an adduction movement and is together defined as inversion.[62]

Shoulder joint

The shoulder joint is a ball-and-socket joint. Movements around three main axes are possible. A movement around the transversal axis is called flexion (lifting the arm in the sagittal plane to the front) or extension (a movement in the opposite direction). A flexion is feasible to perform up to an angle of approx. 180°, an extension only up to 50°. Movements around the sagittal axis are defined as abduction (the arm is moved away from the body) and adduction (the arm is moved towards the body). Abduction movements are possible up to an angle of approx. 180°. A pure adduction out of neutral pose is prevented by the trunk. However, an adduction together with a flexion is possible up to an angle of about 45°, in combination with an extension only up to a few degrees. Moreover, motions around the longitudinal axis of the arm are possible. Internal rotations (rotations towards the body; seen from the front) and external rotations (rotations

[60] Kapandji, pp. 66-72.
[61] Kapandji, pp. 150-152.
[62] Kapandji, p. 168.

in the opposite direction) are executable in each position of the shoulder joint. An external rotation out of neutral pose is possible up to 80°, an internal rotation (together with an extension in order to lead the arm behind the upper body) up to approx. 110°.[63]

Elbow joint

The elbow joint consists of three joints that are together enclosed by a joint capsule. A hinge joint connects the upper arm with the ulnar and allows a flexion/extension movement of the forearm related to the upper arm. A ball joint connects the upper arm and the radius. Since ligaments ensure a fixation of the ulnar to the radius, only flexion/extension movements of the forearm related to the upper arm and rotational movements, but no abduction/adduction movements, are possible. The third joint is a pivot joint that connects ulnar and radius and allows a rotation of the forearm. As a whole, the elbow joint is a modified hinge joint that allows a flexion/extension movement of the forearm related to the upper arm and a rotational movement of the radius related to the ulnar. A flexion is executable up to 150°, an extension is usually not possible. Sometimes, a hyperextension up to approx. 10° is possible, especially for women and children. Rotational movements are feasible in both directions up to angles of 80-90°.[64]

[63] Kapandji, pp. 2-8.
[64] DocCheck Flexikon – Das Medizinlexikon zum Medmachen. (2015). Ellenbogengelenk.

3 Methods

This chapter will present the methodological approach of the work. It will describe the recording and tracking of movements as well as the statistical methods that are used to quantify the accuracy of markerless and hybrid tracking against marker-based tracking.

3.1 Recording and tracking settings, calculated data and filtering

For all recordings, a camera set up of 8 synchronized high speed cameras was used. All movements were recorded with a frame rate of 100 frames per second (fps). Either markers according to a full body inverse kinematic or a lower body marker set were attached to the captured subject. The same recordings were used for marker-based tracking in Simi Motion and silhouette-based or hybrid tracking in Simi Shape. Figure 11 shows the tracking settings that are used for all markerless and hybrid trackings in this work (see chapter 2.2.4 for explanations). For hybrid trackings, additionally the parameter ‘use 3D-marker-correspondences’ was activated and, for most hybrid trackings, the weight for silhouette-correspondences was set to 20 (see chapter 3.5).

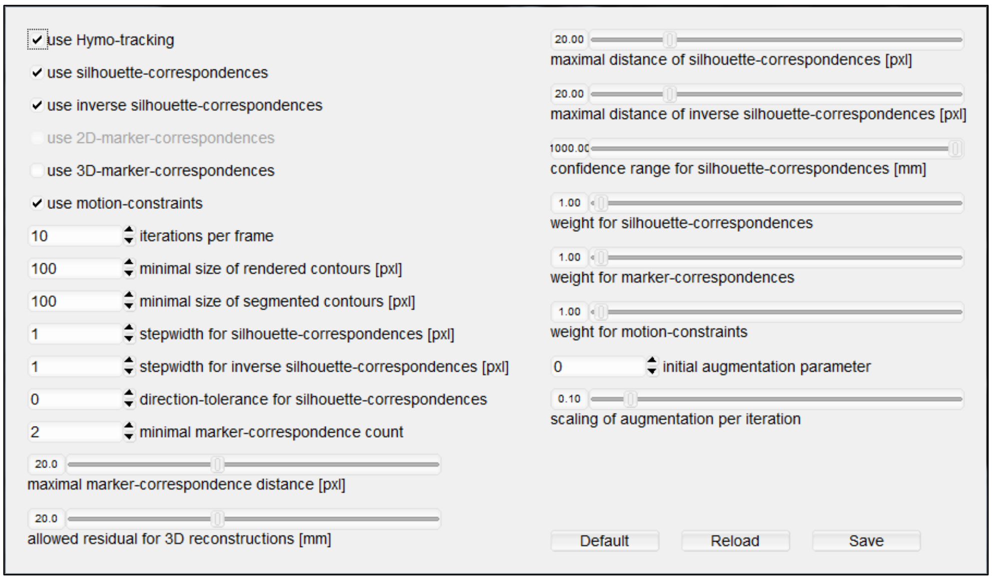

Figure 11: Tracking settings for markerless and hybrid tracking.

Inverse kinematic data were calculated and joint angle data were filtered with a 6 Hz 2nd order low pass filter that is suggested by Richards (2008) for walking data. For faster movements, he recommends using higher cut-off frequencies.[65] Dal Pupo et al.

[65] Richards, J. (2008). Biomechanics in clinic and research. Churchill Livingstone, p. 114.

(2013)[66] as well as Willson et al. (2008)[67] use a cut-off frequency of 10 Hz for analyzing jumping movements. For this study, the effect of different filter frequencies on joint angle data was tested. Therefore, statistical values that are used in this work to compare markerless and hybrid data to marker-based data (correlation coefficient and SD of angle difference, see chapter 3.2) were calculated with both, using data filtered with a frequency of 6 Hz and 10 Hz for a jumping sequence. Results show a mean deviation of correlation of 0.005 (± 0.005) and a mean deviation of SD of 0.06° (± 0.03°) over all joint angles.[68] Due to these very small differences, a filter frequency of 6 Hz was chosen to be applied for all movements to facilitate data filtering by using the same analysis routine. The filtered joint angle data were then exported.[69]
The accuracy of silhouette-based and hybrid tracking was analyzed against marker-based tracking by comparing joint angle data using the statistical methods presented in chapter 3.2. The following joint angles were examined:

- hip: flexion/extension, abduction/adduction, internal/external rotation
- knee: flexion/extension
- ankle: plantar/dorsal flexion, eversion/inversion, abduction/adduction
- shoulder: flexion/extension, abduction/adduction, internal/external rotation
- elbow: flexion/extension

For knee and elbow joints, only flexion/extension movements were analyzed because these joints own only one degree of freedom in the Shape model. Hand movements were not regarded as the current Shape model does not have a precise but rather round hand segment and is therefore not possible to be tracked markerless (Figure 12).

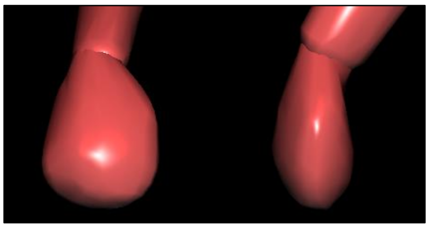

Figure 12: Hand of the Shape model (front and side view).

[66] Dal Pupo, J., Dias, J. A., Gueller, R. G., Detanico, D. and Dos Santos, S. G. (2013). Performance and intralimb coordination during a continuous vertical jump test. XXIV Congress of the International Society of Biomechanics, XV Brazilian Congress of Biomechanics.
[67] Willson, J. D., Binder-Macleod, S. and Davis, I. S. (2008). Lower Extremity Jumping Mechanics of Female Athletes With and Without Patellofemoral Pain Before and After Exertion. American Journal of Sport Medicine, 36(8), pp. 1587-1596. doi: 10.1177/0363546508315592.
[68] For more detailed statistics see Appendix B.1.
[69] A more in detail description of data export and processing is presented in Appendix B.2.

3.2 Statistical methods

To quantify the accuracy of markerless and hybrid tracking against marker-based tracking, the following statistical values were calculated (using Microsoft Excel 2010 and IBM SPSS Statistics 20):

1. Spearman correlation coefficient: Data samples were tested for normality and turned out to be not normally distributed.[70] The spearman correlation coefficient is a nonparametric test that measures the dependence of two variables. It only uses ranks and does not require normally distributed data.[71] The interpretation of the correlation coefficient is presented in Table 6.

Table 6: Interpretation of the correlation coefficient.[72]

Correlation	Interpretation
$r \geq$ **0.9**	very high correlation
$0.7 \leq r < 0.9$	high correlation
$0.5 \leq r < 0.7$	moderately strong correlation
$r < 0.5$	weak correlation

2. Angle range difference: The angle ranges (highest value minus lowest value) of both the marker-based tracking data and the silhouette-based resp. hybrid tracking data were calculated. The difference of both represents the angle range difference. Problem: For all in all good tracking data with a small angle range difference, just one discordant value might lead to a high angle range difference.
3. Mean value (MV) of angle difference: For each frame of the recorded movement, the angle difference was measured and the mean value over all angle differences was calculated. Problem: A high mean value does not always mean a bad markerless tracking. It might just be caused by a constant offset which can occur because of differently defined coordinate systems in the Motion and the Shape model.
4. Standard deviation of angle difference: The standard deviation of the angle difference was calculated. In the studies presented in chapter 1.2.2, angle deviations that are smaller than 5° are stated by the authors to provide good results resp. an applicability of the markerless tracking approch. Accordingly, standard deviations of < 5° are defined as small in this study.

[70] See Appendix C.1, Table 34 - Table 35.
[71] Doane, D. P. and Seward, L. E. (2013). Applied statistics in business and economics, 4th edition. New York: McGraw-Hill, p. 709.
[72] Based on Jakob, B. (2002). Korrelation. Universität Stuttgart.

The correlation coefficient and the standard deviation of angle difference are the most significant values to evaluate the accuracy of markerless and hybrid tracking against marker-based tracking. The correlation coefficient determines how consistent the angle progresses are, not regarding the exact values, e.g. amplitudes. The standard deviation shows how consistent the angle differences are. For example, consistent angle progressions of markerless and marker-based data with highly different amplitudes cause a very high correlation and a high standard deviation of angle difference. That is why these two statistical values were used for further evaluation.

3.3 Description of recorded movements

In the following, the recordings that were used for analysis are described. These recordings were tracked marker-based, markerless and as a hybrid tracking (see chapter 3.5). Afterwards, the results of markerless and hybrid tracking were evaluated against marker-based tracking results using the statistical methods presented in chapter 3.2.

Specific joint movements

As a first step, specific joint movements were recorded. One subject performed movements in all joints and planes that are mentioned in chapter 3.1. All 11 movements were performed with extremities of the right and left body side as well as with big and small ranges of motion. Angle ranges of less than 5° are defined as small. [73] Big movements show angle ranges that are ≥ 15°. All in all, 44 movements with 595 ± 129 frames were conducted.

Complex movements

As a next step, recordings of different complex movements performed by three different subjects were tracked marker-based in Simi Motion and markerless in Simi Shape. Every movement was only performed by one subject. Four of these recordings were made with a full body inverse kinematic marker set: biking on a stationary bike, running, separated in running with big steps and running with small steps, kicks and box punches and jumping, categorized in jumps on both legs, jumps on the right leg and jumps on the left leg. Additionally, two recordings that were made with a marker set for lower extremities were analyzed: jumping jack movements and once again jumping movements which include jumps on both legs, jumps on the right leg, jumps on the left leg and jumps on alternating legs. In total, there are 12 movements, 7 with a full body marker set and 5 with a lower body marker set, with 278 ± 229 frames that were used for analysis.

[73] According to standard deviations of angle difference that are defined to be small if they are < 5°.

3.4 Problem analysis: Identification of markerless tracking problems

The results that were obtained by comparing markerless to marker-based tracking of specific joint movements were used to identify markerless tracking problems. Movements with correlations and/or standard deviations of angle difference that are not very good (very high correlation: $r \geq 0.9$; very good standard deviation: $SD < 5°$) were analyzed more closely to find out the reasons for markerless tracking problems.

First, it was analyzed which segment (every joint is built up of two body segments) causes the problems. Simi Motion offers the possibility to represent the calculated inverse kinematic data using a skeleton representation view and the opportunity to display segment coordinate systems. To compare the calculated inverse kinematic data of markerless and marker-based tracking, the possibility of overlaying two skeletons (one displayed with inverse kinematic data of markerless and one of marker-based tracking) and visually comparing segment rotations by regarding segment coordinate axes was used (Figure 13).

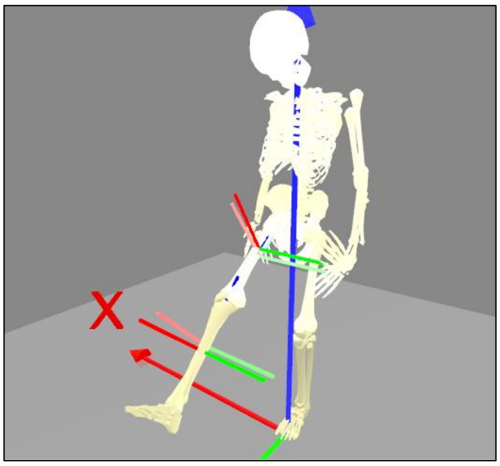

Figure 13: Overlayed inverse kinematic data of marker-based and markerless tracking. Segment coordinate axes are displayed: The dark colors represent the marker-based data, the light colors the markerless data (red: local x-axes, green: local y-axes, blue: local z-axes).

Additionally, a quantitative method was used to find out which segment causes tracking problems[45]: Every joint angle is determined by the rotations of the two body segments that build the joint. To figure out if joint angle differences between marker-based and markerless tracking are caused by tracking problems of the proximal or the distal segment, the proximal segment rotations of marker-based and markerless tracking were compared as well as the distal segment rotations. The following mathematical methods were used (explained by means of the example of the hip joint):

1. A rotation of a segment in a three-dimensional space can be represented by rotations around the global coordinate axes by certain angles. It can also be defined by a rotation around an axis that goes through the origin of the global coordinate system but is usually not consistent with one of the global coordinate axes. Simi Motion offers a function to represent rotations of body segments. As a result, a vector with x, y, z coordinates is given. This vector starts in the origin of the global coordinate system and ends in the point defined by the x, y, z coordinates. It indicates the direction of the axis around which the global coordinate system has to be rotated to be transferred into the local coordinate system of the segment. The length of this vector indicates the rotation angle. This approach was applied for both the marker-based and the markerless data and for both segments that build the joint (e.g. pelvis and thigh).
2. As a second step, the previously obtained vector was normalized by first calculating the norm of the vector[74]:

$$|\vec{a}| = \sqrt{{a_x}^2 + {a_y}^2 + {a_z}^2} \tag{4.1}$$

   and then dividing the original vector by its norm[74]:

$$a_n = \frac{\vec{a}}{|\vec{a}|} \tag{4.2}$$

   The normalized vector represents the direction of the axis around which the global coordinate system has to be rotated to be transferred into the local coordinate system without information about the rotation angle. The norm of the vector indicates the angle by which the coordinate system has to be rotated around this axis. Once again, this was calculated for marker-based and markerless data and for both segments.
3. Then, the dot product[74]

$$\vec{a} \cdot \vec{b} = a_x \cdot b_x + a_y \cdot b_y + a_z \cdot b_z \tag{4.3}$$

   between the normalized vectors of the marker-based and the markerless data (separately for each segment) was calculated and the inverse cosine function was applied to get the axis angles between the rotation axes of marker-based and markerless data. An angle of 0° would indicate a pelvis resp. thigh rotation of marker-based and markerless tracking about the exact same axis.

[74] Bartsch, H.-J. and Sachs, M. (2015). Kleine Formelsammlung Mathematik, 6. edition. Carl Hanser Verlag, pp. 49-50.

4. By calculating the difference between the previously calculated norms of the vectors (separately for both segments), the angle difference between the angles by that the global coordinate system has to be rotated to be transferred into the local coordinate system of the marker-based data and of the markerless data was determined. An angle difference of 0° would indicate a rotation by the same angle. This difference was calculated for both segments.
5. The mean values and standard deviations over all samples of the analyzed part of the recording (e.g. the part of big hip flexion/extension movements) were calculated. These values were compared between the two segments that build the joint (e.g. pelvis and thigh of the hip joint). As a constant offset of coordinate systems does not mean a bad tracking, the standard deviation is the value to be compared. A high standard deviation of ‘axis angle’ and of ‘rotation angle difference’ indicates a tracking problem of this segment.

Since these calculated data only represent the entire segment rotations, not distinguished by the kind of joint movement, results are only a hint to which segment is the problematic one that causes tracking problems. E.g. for hip flexion/extension angles: an incorrect rotational movement of the thigh causes bad ‘axis angle’ and ‘rotation angle difference’ values, but has no negative effect on hip flexion/extension angles.

3.5 Hybrid tracking settings and selection of marker combinations

To enable a good tracking also for joint angles that are affected by pure silhouette-based tracking problems, the possibility of hybrid tracking can be used. The results of the problem analysis that are described in chapter 4.1.2 indicate which body segments cause tracking problems for which joint angles. As a consequence, the problematic segments have to be supported by initializing a few additional markers as a hybrid tracking variant to make a reliable tracking possible. The placement of the markers was chosen in a way that the attached markers are not located on or on a line parallel to the axis around which tracking problems for the regarded movement occur. For example, for ankle plantar/dorsal flexion motions, two markers at the ankles cannot help to improve the tracking.

For all hybrid trackings, the weight for silhouette-correspondences was set 20-fold higher than for marker-correspondences. For tracking of complex hip rotation movements with three pelvis and med. and lat. knee markers, also a tracking with equally set silhouette- and marker-correspondences was conducted (see chapter 2.2.4).

Specific joint movements

Different marker combinations were tested for the recorded specific joint movements with big angle ranges (Table 7). The following criteria were considered to choose marker combinations:

1. As few markers as possible
2. Markers that can easily be tracked, meaning that they are good visible and rarely covered by body parts

Table 7: Tested hybrid tracking marker combinations for specific joint movements with big angle ranges.

Joint	Movement	Markers
hip	flexion/extension	3 pelvis (spina right and left, mid spina)
	abduction/adduction	3 pelvis (spina right and left, mid spina)
	rotation	3 pelvis (spina right and left, mid spina), lat. knee
		3 pelvis (spina right and left, mid spina), lat. and med. knee
ankle	plantar/dorsal flexion	forefoot
		forefoot, heel
	eversion/inversion	lat. ankle
		lat. and med. ankle
	abduction/adduction	lat. knee
		lat. and med. knee
		lat. and med. knee, forefoot
		lat. and med. knee, forefoot, heel
shoulder	abduction/adduction	triceps
		lat. elbow, triceps
	rotation	triceps
		lat. elbow, triceps
elbow	flexion/extension	triceps
		lat. elbow, triceps
		lat. elbow, triceps, lat. and med. wrist

Complex movements

Combinations that were found to be very good for the tracking of specific joint movements, which are all hybrid tracking variants according to Table 7 except of only one lat. knee marker for ankle abduction/adduction movements and one triceps marker for shoulder abduction/adduction movements, were then tested for all complex movements.

3.6 Elimination of problems that are not tracking-based

Since the results (see chapter 4.1.1.2) show that markerless data of small joint movements (< 5°) cannot be compared to marker-based data with the camera setup that was used in this work, joint angle data of complex movements were cut: The movements were divided into parts of 50 frames. Each part with an angle range of less than 5° was cut off (angle ranges of marker-based data were considered). This approach was applied for all samples that have a correlation of less than 0.9 and was applied for markerless as well as for hybrid data.

If there are still big differences comparing hybrid tracking data with marker-based data, the reason might be the use of two different human models. To find out if this is the case, the full marker set was initialized for tracking in Simi Shape. Furthermore, silhouette-correspondences were deactivated so that only marker-correspondences were used for tracking with the Shape model. The obtained joint angle data were compared to hybrid tracking data.

4 Results

In the following chapter, the results of the study will be presented.[75]

4.1 Markerless tracking compared to marker-based tracking

The results of markerless tracking of, first, specific joint movements and, second, complex movements compared to marker-based tracking data are shown.

4.1.1 Specific joint movements

Specific joint movements with big and small ranges of motion were recorded (see chapter 3.3). In the following, the results of markerless compared to marker-based tracking are presented.

4.1.1.1 Big ranges of motion

Table 8 shows the correlations and standard deviations of angle difference for joint movements with big amplitudes.[76]

Table 8: Correlations and standard deviations of angle difference of specific joint movements with big ranges of motion comparing markerless and marker-based data. First value for the right, second value for the left body side. Correlations that are ≥ 0.9 for both body sides are highlighted in green, those that are ≥ 0.7 in yellow and correlations of less than 0.7 (for one or both body sides) are highlighted in red.

Joint	Movement	Correlation	SD angle diff. [°]
hip	flexion/extension	0.86 / 0.91	14.5 / 18.6
	abduction/adduction	0.97 / 0.98	5.4 / 2.8
	rotation	0.93 / 0.93	10.4 / 6.6
knee	flexion/extension	1.00 / 1.00	3.3 / 4.5
ankle	plantar/dorsal flexion	0.98 / 0.96	3.9 / 5.5
	eversion/inversion	0.39 / 0.81	5.5 / 4.1
	abduction/adduction	0.58 / 0.90	7.9 / 5.6
shoulder	flexion/extension	1.00 / 1.00	7.4 / 14.4
	abduction/adduction	0.88 / 0.78	9.9 / 13.3
	rotation	0.90 / -0.10	14.5 / 24.6
elbow	flexion/extension	1.00/ -0.99	5.9 / 106.4

[75] If not stated otherwise, correlations are significant on a significance value of $p \leq 0.01$.
[76] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.2, Table 36.

Perfect correlations of 1.0 for both sides between marker-based and markerless tracking data are found in knee and shoulder flexion/extension angles. Knee angles, unlike shoulder angles, also show very small standard deviations. Knee angle progressions are presented in Figure 14.

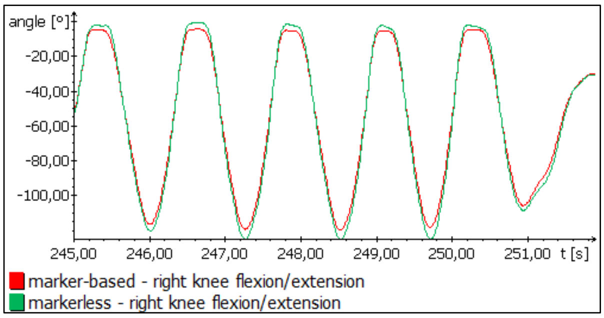

Figure 14: Knee flexion/extension angle progressions (right ankle) of marker-based and markerless tracking.

Also very high correlations occur in ankle plantar/dorsal flexion movements, hip abduction/adduction and hip rotation movements with standard deviations that are higher than 5° for at least one body side though. Hip flexion/extension as well as shoulder abduction/adduction movements show correlations that are higher than 0.7 for both body sides and high standard deviations of angle difference. Ankle eversion/inversion and abduction/adduction, shoulder abduction/adduction and elbow flexion/extension movements show a worse correlation than 0.7 for at least one side. As only the knee shows very good results in both correlations and standard deviations of angle difference for both body side trials, all other movements were analyzed more closely to identify markerless tracking problems (see chapter 4.1.2).

4.1.1.2 Small ranges of motion

Table 9 presents the statistical data of specific joint movements with small ranges of motion.[77]

[77] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.2, Table 37.

Table 9: Correlations and the standard deviations of angle difference of specific joint movements with small ranges of motion comparing markerless and marker-based data. First value for the right, second value for the left body side.

Joint	Movement	Correlation	SD angle diff. [°]
hip	flexion/extension	0.17 / -0.24	3.1 / 2.9
	abduction/adduction	0.13 / 0.60	1.6 / 2.2
	rotation	0.10 / 0.24	2.0 / 4.1
knee	flexion/extension	0.33 / 0.38	0.8 / 0.8
ankle	plantar/dorsal flexion	0.17 / 0.15	1.5 / 1.9
	eversion/inversion	0.02 / 0.32	3.4 / 1.3
	abduction/adduction	0.04 / 0.31	1.9 / 3.1
shoulder	flexion/extension	0.49 / 0.73	1.3 / 1.8
	abduction/adduction	0.33 / 0.11	1.0 / 1.2
	rotation	0.37 / -0.17	3.8 / 7.9
elbow	flexion/extension	0.25 / -0.16	1.4 / 1.0

There is no small joint movement with an angle range of less than 5° that shows a high correlation. For each joint movement, for at least one body side the correlation is smaller than 0.5.

4.1.2 Problem analysis: Identification of markerless tracking problems

As shown in the previous part, markerless data of small joint movements cannot be compared to marker-based data in this work. The reason is presented in chapter 5.2.2. In the following, problems of markerless tracking of movements with big ranges of motion will be pointed out.

Hip

Table 10 reports the standard deviations of ‘axis angle’ and ‘rotation angle difference’ (see chapter 3.4) of the pelvis and the thigh for all specific hip movements.

Table 10: Standard deviations of ‘axis angle‘ and ‘rotation angle difference‘ for the pelvis and thigh segments regarding specific hip movements.

Movement	SD 'axis angle' [°]		SD 'rotation angle difference' [°]	
	pelvis	thigh	pelvis	thigh
flexion/extension right	4.5	2.2	6.1	4.5
flexion/extension left	4.3	2.6	8.1	5.0
abduction/adduction right	3.6	8.0	8.9	12.0
abduction/adduction left	3.3	4.1	4.8	9.8
rotation right	3.2	2.6	3.3	7.2
rotation left	3.1	1.1	6.8	4.2
mean value	**3.7**	**3.4**	**6.3**	**7.1**

The movements in different planes do not have to be regarded separately since these values represent the whole segment rotations (not separated by planes). Regarding the mean values, there is no significant difference between the pelvis and the thigh segment. Therefore, it can be assumed that both segments cause problems that affect results of markerless tracking of hip movements without knowing for which movements exactly. Thus, the visual method of comparing inverse kinematic data of marker-based and markerless tracking that is explained in chapter 3.4 was used to identify specific problems for all of the three kinds of joint movement.

Flexion/extension and abduction/adduction

Figure 15 shows the angle progressions of marker-based and markerless tracking of hip flexion/extension movements and two close points of time. Additionally, the skeletons of both data are overlayed and segment axes are displayed.

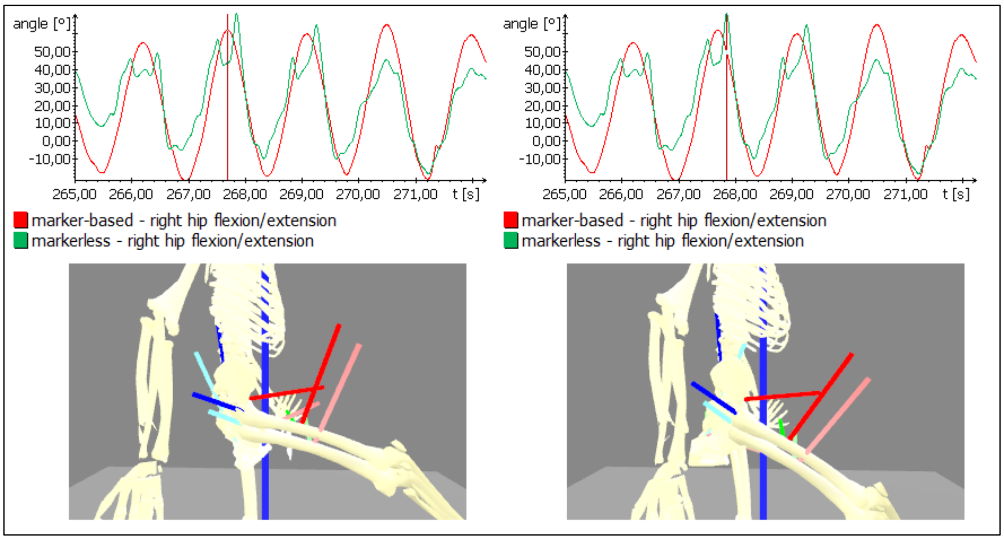

Figure 15: Hip flexion/extension angles (right hip) of marker-based and markerless tracking for two close points of time and corresponding inverse kinematic data represented as a skeleton overlay. Dark colored segment axes belong to marker-based data, light colored to markerless data.

The light colored axes of the markerless data (e.g. the light blue z-axis) show a tilt of the pelvis in the sagittal plane, whereas the marker-based tracked pelvis remains stable. This causes the incorrect, uneven progress of the hip flexion angle that can be seen in Figure 15. In contrast, the flexion/extension movement of the thigh is very similar for marker-based and markerless data. The same, but less strong, effect is observed for hip abduction/adduction and rotation movements.

Rotation

Figure 16 shows angle data and skeleton overlay views of rotational movements of the right hip.

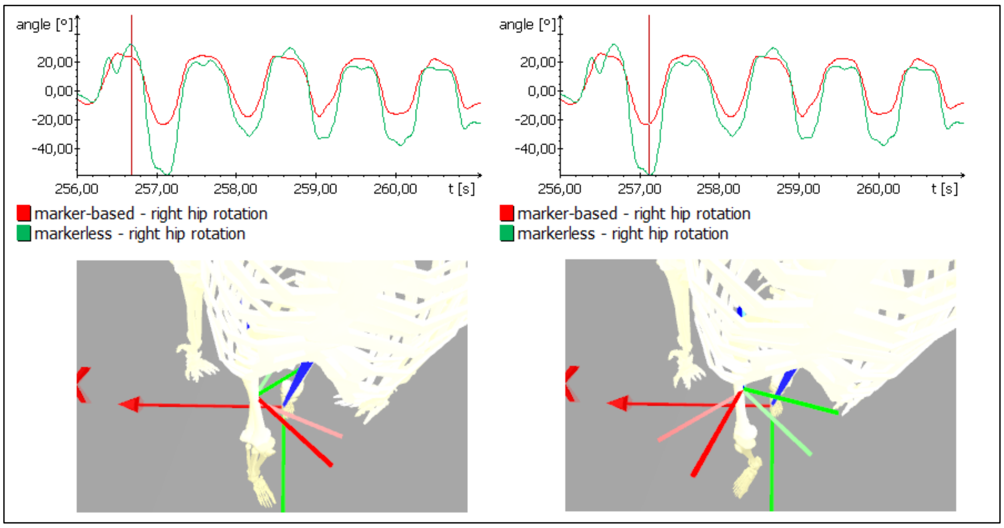

Figure 16: Hip rotation angles (right hip) of marker-based and markerless tracking for two close points of time and corresponding inverse kinematic data represented as a skeleton overlay. Dark colored segment axes belong to marker-based data, light colored to markerless data.

As the green graph and the light red x-axis of markerless tracking data indicate, the rotational movements of the markerless tracking are less even and have much higher ranges of motion than those of the marker-based tracking. This is because the silhouette of the leg barely changes during rotation and consequently these motions cannot be tracked accurately markerless.

Summarizing the results of markerless tracking of hip angles, it can be concluded that the pelvis is critical for movements in all planes. Additionally, the thigh shows problems in tracking of rotational movements.

Ankle

In Table 11, the standard deviations of ‘axis angle’ and ‘rotation angle difference’ of the shank and the foot for all specific ankle movements are presented.

Table 11: Standard deviations of ‘axis angle‘ and ‘rotation angle difference‘ for the shank and foot segments regarding specific ankle movements.

Movement	SD 'axis angle' [°]		SD 'rotation angle difference' [°]	
	shank	foot	shank	foot
plantar/dorsal flexion right	1.5	2.6	11.5	3.5
plantar/dorsal flexion left	2.1	5.0	6.1	4.1
eversion/inversion right	0.6	1.8	6.7	1.3
eversion/inversion left	0.4	2.4	2.7	2.2
abduction/adduction right	0.8	3.2	7.2	1.6
abduction/adduction left	0.6	3.1	6.0	2.0
mean value	**1.0**	**3.0**	**6.7**	**2.4**

Comparable to the pelvis and thigh segments of the hip joint, a clear conclusion which segment is responsible for markerless tracking problems cannot be made. The foot segment shows higher standard deviations of ‘axis angle’ values, the shank segment of ‘rotation angle difference’ values. Probably both segments cause tracking problems that will be analyzed by visual examination in the following.

Plantar/dorsal flexion

Figure 17 shows the angle progressions of marker-based and markerless plantar/dorsal flexion movements of the left ankle.

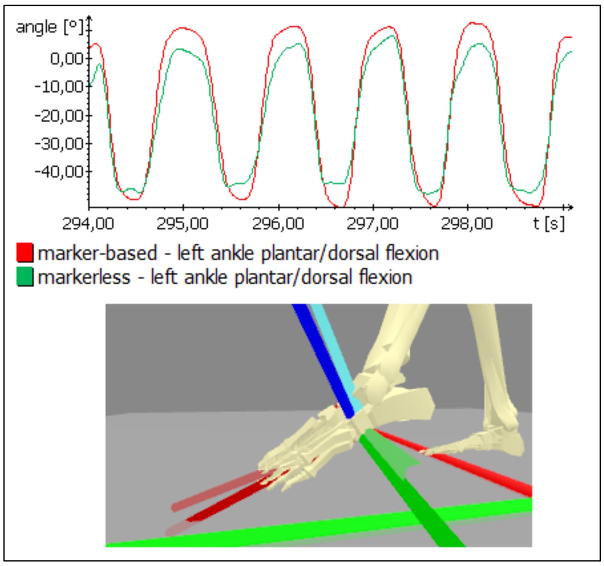

Figure 17: Ankle plantar/dorsal flexion angles (left ankle) of marker-based and markerless tracking and corresponding inverse kinematic data represented as a skeleton overlay. Dark colored segment axes belong to marker-based data, light colored to markerless data.

The correlation between both movements is very high (r = 0.96), the standard deviation of angle difference is 5.5°. The reason for these angle differences is caused by the foot that is able to slightly move within the silhouette.

Eversion/inversion

The angle progressions of marker-based and markerless tracking of the right ankle are presented in Figure 18.

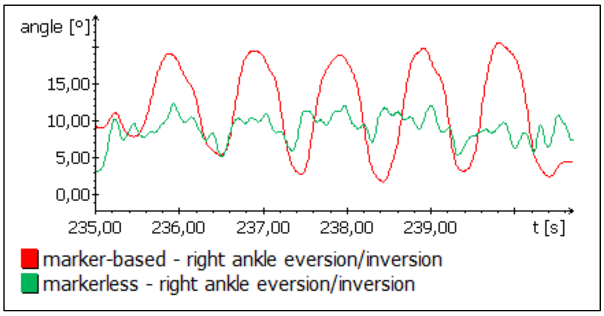

Figure 18: Ankle eversion/inversion angles (right ankle) of marker-based and markerless tracking.

The correlation coefficient is 0.39. The foot is the segment that is difficult to track here as the silhouette barely changes performing eversion/inversion movements.

Abduction/adduction

In Figure 19, marker-based and markerless angles of abduction/adduction movements are shown.

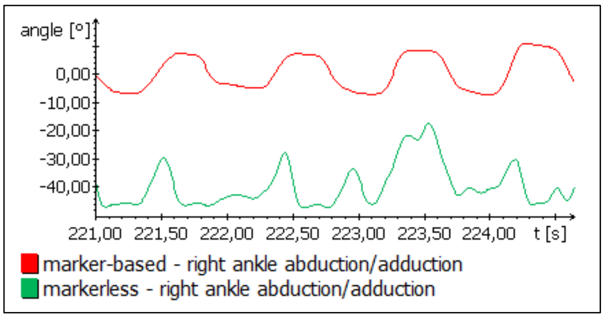

Figure 19: Ankle abduction/adduction angles (right ankle) of marker-based and markerless tracking.

The skeleton overlay shows a rather consistent movement of the foot between the Motion and the Shape model. On the contrary, the shank rotation of the Shape model is very inconsistent and different to that of the Motion model.[78] Therefore, the shank segment is very likely to cause the weak correlation of r = 0.58. The foot, however, is likely to cause small problems that affect angle differences similarly to plantar/dorsal flexion movements as the foot is able to slightly move within the silhouette.

Summarizing problems of markerless tracking of ankle movements, the foot segment seems to cause weak correlations for eversion/inversion movements and the shank rotation is the main problem for tracking of abduction/adduction movements. Smaller problems occur for markerless tracking of plantar/dorsal flexion and abduction/adduction movements that are caused by the foot segment.

Shoulder

Table 12 reports the standard deviations of ‘axis angle’ and ‘rotation angle difference’ of the upper arm and the thorax for all specific shoulder movements.

[78] The skeleton view is not presented here as the inconsistent movements of the shank are too small to be recognized by only looking at still images.

Table 12: Standard deviations of 'axis angle' and 'rotation angle difference' for the upper arm and thorax segments regarding specific shoulder movements.

Movement	**SD 'axis angle' [°]**		**SD 'rotation angle difference' [°]**	
	upper arm	**thorax**	**upper arm**	**thorax**
flexion/extension right	24.9	1.4	16.8	1.6
flexion/extension left	28.9	0.9	16.20	2.4
abduction/adduction right	20.4	0.8	18.6	2.7
abduction/adduction left	10.0	0.8	20.1	4.1
rotation right	4.8	0.5	11.1	1.3
rotation left	7.1	0.5	16.8	0.8
mean value	**16.0**	**0.8**	**16.7**	**2.1**

In this case, the standard deviations of the upper arm are much higher than those of the thorax which are very small. Hence, it is obvious that incorrect motions of the upper arm and not of the thorax cause markerless tracking problems.

Flexion/extension

In Figure 20, the angle progressions of the shoulder flexion/extension movements are presented.

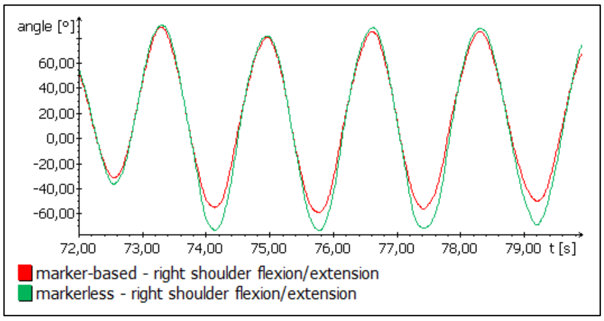

Figure 20: Shoulder flexion/extension angles (right shoulder) of marker-based and markerless tracking.

They show perfect correlations but high standard deviations of angle difference (7.4° for the right and 14.4° for the left side). These angle differences are caused by differently defined shoulder joint centers in the two models as Figure 21 illustrates.

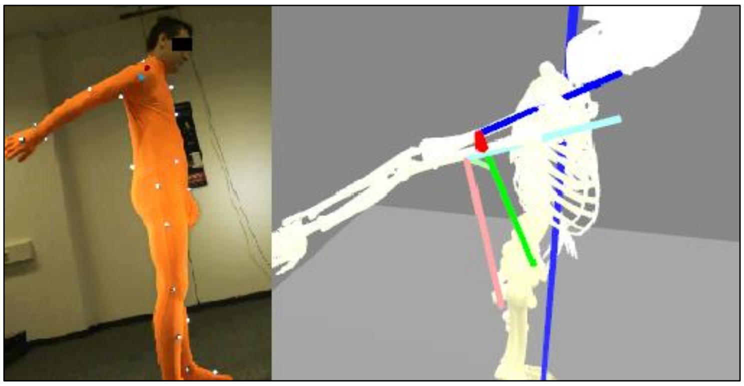

Figure 21: Differently defined shoulder joint centers of the Motion model (dark red spot in the left picture, dark blue upper arm segment axis in the right picture) and the Shape model (light blue spot and segment axis).

Abduction/adduction

Figure 22 presents angle data of shoulder abduction/adduction movements. For both marker-based and markerless data the absolute angle value decreases although, regarding the skeleton view, the shoulder abduction increases.

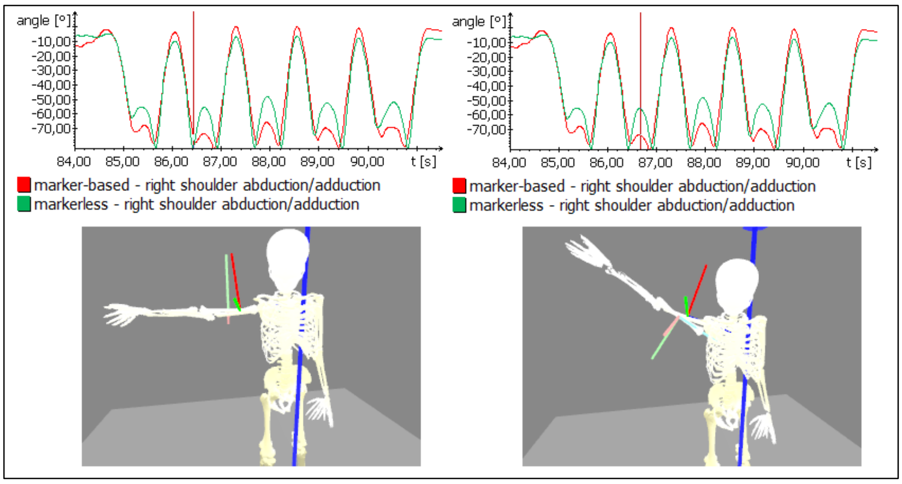

Figure 22: Shoulder abduction/adduction angles (right shoulder) of marker-based and markerless tracking for two close points of time and corresponding inverse kinematic data represented as a skeleton overlay. Dark colored segment axes belong to marker-based data, light colored to markerless data.

This is due to the representation of rotations as Cardan angles. The shoulder abduction/adduction movement is a combination of first, a rotation around the x-axis of the upper arm joint coordinate system, which is similar to a shoulder flexion/extension movement, and second, a rotation around the y-axis of the previously rotated joint coordinate system. In this presented case of shoulder abduction/adduction movement, until an angle of approx. 60°, the movement is performed as a pure abduction. For increasing abduction, the flexion angle starts to increase. At a visually assessed abduction angle of

90°, the movement is performed as an approx. 30° flexion and 80° abduction movement. For further movement, the flexion angle increases up to approx. 130° and thus, the abduction angle decreases to approx. 70° (Figure 23).

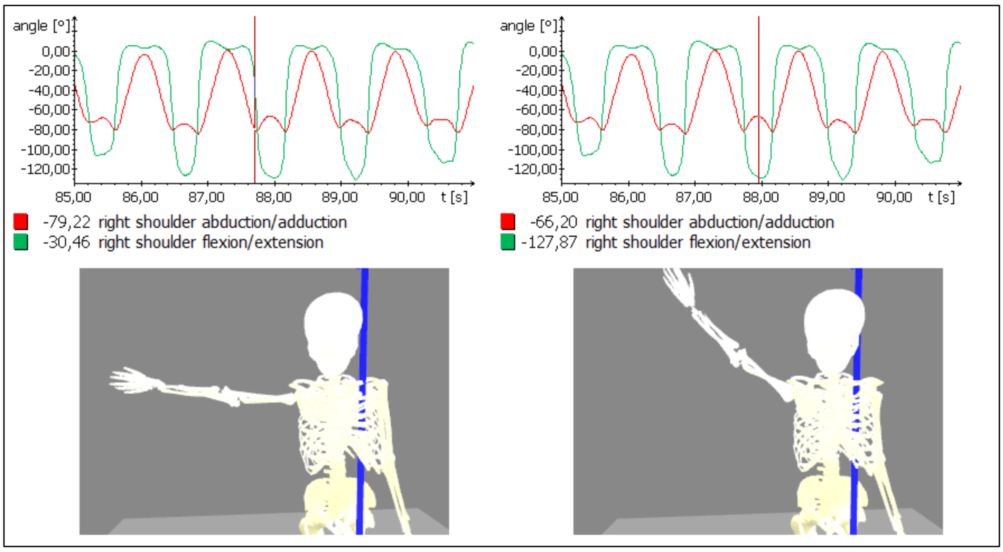

Figure 23: Shoulder abduction/adduction and flexion/extension angles (marker-based data) of abduction movement of the right shoulder for two close points of time. Corresponding inverse kinematic data represented as a skeleton view.

Besides the problem of Cardan angles, similar to flexion/extension movements, the differently defined shoulder centers of the Motion and the Shape model affect abduction/adduction angles. Furthermore, for markerless tracking, the model arm (especially for big adduction angles) is able to tilt within the silhouette which also causes angle differences compared to marker-based tracking data.

Rotation

The angle progressions of rotational movements of marker-based and markerless tracking are illustrated in Figure 24.

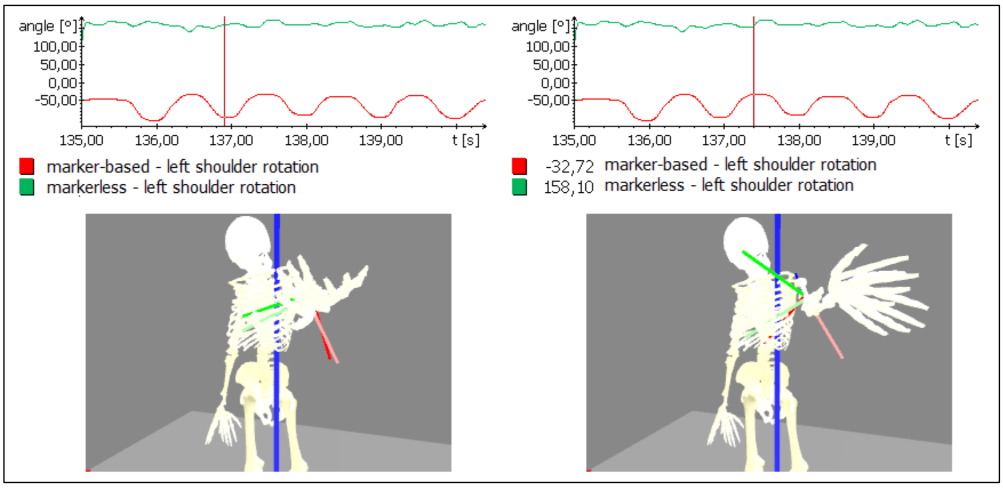

Figure 24: Shoulder rotation angles (left shoulder) of marker-based and markerless tracking for two close points of time and corresponding inverse kinematic data represented as a skeleton overlay. Dark colored segment axes belong to marker-based data, light colored to markerless data.

Observing the red x-axes, it can be seen that a shoulder rotation is performed by the Motion model but not by the Shape model. Similarly to the hip rotation movements, the reason for markerless shoulder rotation tracking problems is the silhouette that barely changes.

Summarizing markerless tracking problems of shoulder movements, the not changing silhouettes during rotations of the upper arm cause problems for tracking of rotational shoulder movements. Furthermore, the possibility of the upper arm to tilt within the silhouette causes smaller problems for abduction/adduction movements. Other factors (differently defined shoulder centers and Cardan angles) that influence flexion/extension and abduction/adduction movements are no tracking problems and therefore cannot be eliminated by hybrid tracking.

Elbow

Table 13 reports the standard deviations of ‘axis angle’ and ‘rotation angle difference’ of the upper arm and the forearm for specific elbow flexion/extension movements.

Table 13: Standard deviations of ‘axis angle‘ and ‘rotation angle difference‘ for the upper arm and forearm segments regarding specific elbow flexion/extension movements.

Movement	**SD 'axis angle' [°]**		**SD 'rotation angle difference' [°]**	
	upper arm	**forearm**	**upper arm**	**forearm**
flexion/extension right	2.9	3.5	3.9	0.9
flexion/extension left	3.0	7.1	5.9	10.7
mean value	**2.9**	**5.3**	**4.9**	**5.8**

Standard deviations are slightly higher for the forearm, but both segments seem to cause markerless tracking problems.

Figure 25 shows the elbow flexion/extension angles of marker-based and markerless tracking.

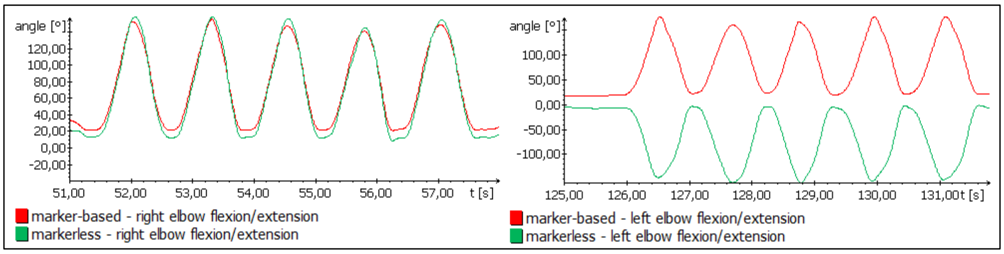

Figure 25: Elbow flexion/extension angles of the right elbow (left graph) and the left elbow (right graph) of marker-based and markerless tracking.

Data of the right body side show a perfect positive, data of the left side a very high negative correlation. High negative correlations occur when the arm strongly rotates in the shoulder joint, since shoulder rotations cannot be tracked markerless and therefore, the elbow executes a hyperextension that is anatomically not possible.

4.1.3 Complex movements

The complex movements that are described in chapter 3.3 were tracked marker-based in Simi Motion and markerless in Simi Shape. Table 14 presents for each joint and kind of joint movement the percentages of very high, high, moderately strong and weak correlations between marker-based and markerless joint angle data as well as the mean values of correlation and those of standard deviation of angle difference over both body sides and all trials of complex movements.[79]

[79] The statistical data of all trials separately can be seen in Appendix C.3, Table 38 - Table 49.

Table 14: Statistics of markerless tracked joint angle data compared to marker-based tracked data for complex movements. Presented are the percentages of very high, high, moderately strong and weak correlations as well as the mean values of correlation and of standard deviation of angle difference and their standard deviations over all trials. Very high correlations are highlighted in green, high correlations in yellow and correlations < 0.7 in red.

Joint	Movement	Correlation r (%)				MV correlation (SD)	MV SD angle diff. [°] (SD)
		≥ 0.9	0.9 > r ≥ 0.7	0.7 > r ≥ 0.5	< 0.5		
hip	flexion/extension	**46**	38	0	17	0.78 (±0.26)	6.3 (±2.9)
	abduction/adduction	**17**	25	25	33	0.53 (±0.37)	4.6 (±1.6)
	rotation	**0**	8	42	50	0.43 (±0.27)	9.2 (±3.5)
knee	flexion/extension	**92**	8	0	0	0.97 (±0.05)	2.6 (±1.1)
ankle	plantar/dorsal flexion	**67**	21	8	4	0.86 (±0.18)	5.4 (±1.9)
	eversion/inversion	**0**	8	21	71	0.24 (±0.37)	5.9 (±2.3)
	abduction/adduction	**0**	17	13	71	0.28 (±0.38)	7.6 (±3.4)
shoulder	flexion/extension	**86**	7	0	7	0.91 (±0.14)	6.3 (±4.1)
	abduction/adduction	**64**	21	7	7	0.86 (±0.17)	2.5 (±1.2)
	rotation	**21**	29	7	43	0.48 (±0.49)	34.1 (±49.7)
elbow	flexion/extension	**36**	21	7	36	0.41 (±0.69)	18.8 (±27.0)

Knee flexion/extension movements show very high correlations (r ≥ 0.9) in 92 % of all trials with an average correlation of 0.97. Very good results are also found in shoulder flexion/extension movements with 86 % of very high correlations and an average correlation of 0.91. Mostly very high correlations occur in ankle plantar/dorsal flexion (67 %) and shoulder abduction/adduction (64 %) movements with correlation mean values of 0.86. Very high correlations in less than 50 % of all cases are found in hip flexion/extension (46 %, mean value: 0.78), elbow flexion/extension (36 %, mean value: 0.41), shoulder rotation (21 %, mean value: 0.48) and hip abduction/adduction (17 %, mean value: 0.53) movements. Hip rotation, ankle eversion/inversion as well as abduction/adduction movements show no very high correlations at all.

The results presented in chapter 4.1.1.2 show that markerless data of small joint movements cannot be compared to marker-based data in this work (see chapter 5.2.2 for the reason). The following part shows the results of markerless tracking compared to marker-based tracking of complex movements excluding parts with small ranges of motion (Table 15).[80]

[80] The statistical data of all trials separately can be seen in Appendix C.4, Table 50 - Table 61.

Table 15: Statistics of markerless tracked joint angle data compared to marker-based tracked data for complex movements excluding parts with small ranges of motion. Presented are the percentages of very high, high, moderately strong and weak correlations as well as the mean values of correlation and standard deviation of angle difference and their standard deviations over all trials.

Joint	Movement	Correlation r (%)				MV correlation (SD)	MV SD angle diff. [°] (SD)
		≥ 0.9	**0.9 > r ≥ 0.7**	**0.7 > r ≥ 0.5**	**< 0.5**		
hip	flexion/extension	**48**	39	0	13	0.82 (±0.21)	6.4 (±2.9)
	abduction/adduction	**21**	26	16	37	0.51 (±0.45)	4.6 (±1.5)
	rotation	**0**	18	23	59	0.41 (±0.32)	9.2 (±3.8)
knee	flexion/extension	**100**	0	0	0	0.98 (±0.03)	2.6 (±1.1)
ankle	plantar/dorsal flexion	**70**	26	4	0	0.91 (±0.08)	5.3 (±2.9)
	eversion/inversion	**0**	10	25	65	0.26 (±0.42)	5.0 (±2.4)
	abduction/adduction	**5**	14	23	59	0.34 (±0.40)	7.2 (±3.9)
shoulder	flexion/extension	**100**	0	0	0	0.96 (±0.02)	7.1 (±3.8)
	abduction/adduction	**75**	17	0	8	0.89 (±0.16)	2.8 (±1.2)
	rotation	**25**	25	8	42	0.49 (±0.50)	39.1 (±51.9)
elbow	flexion/extension	**38**	23	8	31	0.42 (±0.70)	20.6 (±28.3)

Regarding knee and shoulder flexion/extension angles, 100 % of all trials show very high correlations with mean values of 0.98 resp. 0.96. The knee, unlike the shoulder, also has a very small mean value of standard deviation of angle difference (2.6°). For ankle plantar/dorsal movements, 96 % of all trials show an at least high correlation, 70 % a very high one. The mean value of correlation over all trials is 0.91, the mean value of standard deviation of angle difference is 5.3°. Shoulder abduction/adduction movements show high correlations in 92 %, very high correlations in 75 % of all cases. The mean value of correlation is 0.89 and standard deviations of angle difference are small. Hip flexion/extension movements have an at least high correlation in 87 % of all cases, a very high one in 48 % and a correlation mean value of 0.82. Standard deviations of angle difference are higher than 5°. All other movements show a mean correlation of less than 0.7.

Figure 26 and Figure 27 show examples (jumping on both legs) of marker-based and markerless data of knee and shoulder flexion/extension angles.

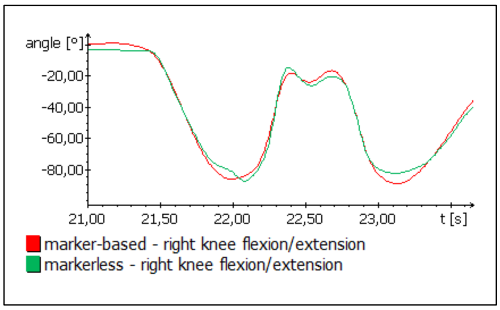

Figure 26: Marker-based and markerless data of knee flexion/extension angles of jumping on both legs (full body marker set).

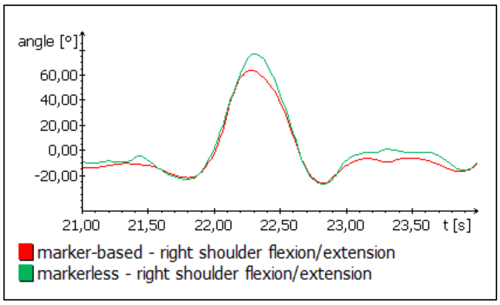

Figure 27: Marker-based and markerless data of shoulder flexion/extension angles of jumping on both legs (full body marker set).

4.2 Hybrid tracking compared to marker-based tracking

In the following, the hybrid tracking results of, first, specific joint movements and, second, complex movements compared to marker-based results are shown.

4.2.1 Specific joint movements

The results of hybrid tracking of specific joint movements using the marker combinations listed in Table 7 are presented.[81]

Hip

For hip flexion/extension and abduction/adduction movements, three pelvis markers were used to stabilize the pelvis. For hip rotation movements, one and two additional knee markers were attached to stabilize rotational movements that cannot be tracked markerless. The results are shown in Table 16.

[81] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.5, Table 62 - Table 65.

Table 16: Statistics of hybrid tracking of hip movements with different marker combinations compared to marker-based tracking. Presented are the correlations and the standard deviations of angle difference of the right (first value) and the left (second value) body side.

Joint	Movement	Markers	Correlation	SD angle diff. [°]
hip	flexion/extension	spina right and left, mid spina	1.00 / 0.99	2.0 / 3.2
	abduction/adduction		0.99 / 0.99	1.9 / 2.0
	rotation	spina right and left, mid spina, lat. knee	0.96 / 0.97	2.6 / 4.0
		spina right and left, mid spina, lat. and med. knee	0.99 / 0.98	1.3 / 3.3

Correlations are very high for all trials. For flexion/extension and abduction/adduction movements, correlations are ≥ 0.99 for both sides. Also the standard deviations of angle difference are very small. For rotational movements, the trials with both knee markers show slightly higher correlations as well as smaller standard deviations than the trial with only one knee marker. Nevertheless, both marker combinations show very good results.

Ankle

For ankle flexion/extension and eversion/inversion movements, the foot has turned out to be the problematic segment. That is why hybrid combinations with one and two foot markers were tested. Additionally, problems in shank rotation tracking affect abduction/adduction angles. Hybrid combinations with one and two knee markers to stabilize these rotations were tested. The markers were chosen in a way that they are not located on or on a line parallel to the rotation axis. Table 17 shows the hybrid tracking results of ankle movements.

Table 17: Statistics of hybrid tracking of ankle movements with different marker combinations compared to marker-based tracking. Presented are the correlations and the standard deviations of angle difference of the right (first value) and the left (second value) body side.

Joint	Movement	Markers	Correlation	SD angle diff. [°]
ankle	plantar/dorsal flexion	forefoot	0.98 / 0.98	3.7 / 3.8
		forefoot, heel	0.99 / 0.99	2.6 / 3.3
	eversion/inversion	lat. ankle	0.94 / 0.91	2.1 / 3.7
		lat. and med. ankle	0.92 / 0.97	3.7 / 2.0
	abduction/adduction	lat. knee	0.89 / 0.93	3.2 / 3.8
		lat. and med. knee	0.92 / 0.96	5.0 / 3.1
		lat. and med. knee, forefoot	0.96 / 0.94	5.8 / 5.6
		lat. and med. knee, forefoot, heel	0.99 / 0.94	6.1 / 5.3

Ankle plantar/dorsal flexion movements show very good results for a hybrid tracking with only one forefoot and with one forefoot and one heel marker. Correlations are 0.98 resp. 0.99 and values for standard deviations of angle difference are less than 5°. Results for ankle eversion/inversion movements are a bit worse but still very good for a tracking with both ankle markers (r = 0.92 resp. 0.97) and also with only one ankle marker (r = 0.94 resp. 0.91). Furthermore, standard deviations of angle difference are small. For abduction/adduction movements, very good results are achieved with both knee markers (r = 0.92 resp. 0.96). Adding one and two foot markers, the correlations get slightly higher (r = 0.96 resp. 0.94 for one forefoot marker and r = 0.99 resp. 0.94 for one forefoot and one heel marker). Nevertheless, the standard deviations of angle difference get a bit higher.

Shoulder

For shoulder abduction/adduction as well as rotational movements, the upper arm appeared to be the problematic segment. Hybrid tracking results are presented in Table 18.

Table 18: Statistics of hybrid tracking of shoulder movements with different marker combinations compared to marker-based tracking. Presented are the correlations and the standard deviations of angle difference of the right (first value) and the left (second value) body side.

Joint	Movement	Markers	Correlation	SD angle diff. [°]
shoulder	abduction/adduction	triceps	0.82 / 0.90	12.6 / 8.2
		lat. elbow, triceps	0.93 / 0.95	7.6 / 5.6
	rotation	triceps	0.99 / 1.00	1.6 / 3.1
		lat. elbow, triceps	0.99 / 0.99	2.4 / 2.4

Using only the triceps marker to support tracking of shoulder abduction/adduction movements leads to correlations of 0.82 resp. 0.90 and high standard deviations of angle difference of 12.6° resp. 8.2°. A hybrid combination with the triceps and the lat. elbow marker improves the correlations to 0.93 resp. 0.95 and decreases the standard deviations to 7.6° resp. 5.6°. For rotational movements, both trackings with one and two markers show very high correlations ($r \geq 0.99$) and small standard deviations ($SD \leq 2.4°$).

Elbow

The main markerless tracking problem of elbow angles is the possibility of the arm to strongly rotate in the shoulder joint which causes negative correlations. One marker attached somewhere to the arm should prevent these big arm rotations. Furthermore, one combination with two arm markers attached to the upper arm and one variant with additionally two markers on the forearm were tested. The results are shown in Table 19.

Table 19: Statistics of hybrid tracking of elbow flexion/extension movements with different marker combinations compared to marker-based tracking. Presented are the correlations and the standard deviations of angle difference of the right (first value) and the left (second value) body side.

Joint	Movement	Markers	Correlation	SD angle diff. [°]
elbow	flexion/extension	triceps	0.99 / 0.99	4.5 / 7.1
		lat. elbow, triceps	0.99 / 0.99	4.1 / 7.1
		lat. elbow, triceps, lat. and med. wrist	1.00 / 0.99	3.6 / 7.1

All three tested marker combinations show very high correlations (r ≥ 0.99). Standard deviations of angle difference are about the same for all combinations (approx. 4° for the right and 7° for the left side).

4.2.2 Complex movements

The previously evaluated marker combinations that show very good results were tested for hybrid tracking of the complex movements.

Hip

Table 20 shows the results of hybrid tracking of the complex movements for hip angles. Presented are the mean values of correlation and their standard deviations over all trials. Additionally, the mean values of standard deviation of angle difference and their standard deviations over all trials are stated.[82]

Table 20: Statistics of hybrid tracking of hip movements with different marker combinations compared to marker-based tracking. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
hip	flexion/extension	spina right and left, mid spina	0.97 (±0.08)	1.7 (±0.8)
	abduction/adduction		0.89 (±0.21)	1.1 (±0.6)
	rotation	spina right and left, mid spina, lat. knee	0.63 (±0.28)	4.7 (±1.9)
		spina right and left, mid spina, lat. and med. knee	0.87 (±0.12)	2.2 (±0.9)

[82] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 66 - Table 68.

Results of flexion/extension movements are very good using three pelvis markers for hybrid tracking with a mean correlation of 0.97. Abduction/adduction movements show a high mean correlation of 0.89 with the same marker combination. Hip rotational movements tracked with three pelvis markers and only one knee marker show a mean correlation of 0.63. Using two knee markers, the correlation improves to 0.87. The mean values of standard deviation of angle difference are less than 5° for every joint movement and marker combination.

Table 21 presents the same statistics for the angle progressions excluding parts with small angle ranges.[83]

Table 21: Statistics of hybrid tracking of hip movements with different marker combinations compared to marker-based tracking excluding parts with small angle ranges. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
hip	flexion/extension	spina right and left, mid spina	0.99 (±0.02)	1.7 (±0.8)
	abduction/adduction		0.94 (±0.09)	1.2 (±0.7)
	rotation	spina right and left, mid spina, lat. knee	0.64 (±0.29)	4.6 (±1.8)
		spina right and left, mid spina, lat. and med. knee	0.91 (±0.06)	2.2 (±0.9)

Hip flexion/extension movements show a nearly perfect correlation of 0.99 for tracking with three pelvis markers. Using the same markers, abduction/adduction movements show a mean correlation of 0.94. Markerless tracking of rotational movements with one knee marker is still problematic. Using two knee markers, a very high mean correlation of 0.91 is reached. Standard deviations of angle difference are small for all movements and marker combinations.

Table 22 shows the statistics of two different tracking settings: a 20-fold weighted silhouette-correspondence comparing to marker-correspondence on the one hand, on the other hand equally weighted silhouette and marker-correspondences (see 2.2.4).[84]

[83] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 69 - Table 71.

[84] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 72 - Table 73.

Table 22: Statistics of hybrid tracking of hip rotational movements with a 20-fold weighted silhouette-correspondence and an equally weighted silhouette- and marker-correspondence compared to marker-based tracking. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

	20-fold silhouette-correspondence		**Equally weighted silhouette- and marker-correspondences**	
	MV correlation (SD)	**MV SD angle diff. [°] (SD)**	**MV correlation (SD)**	**MV SD angle diff. [°] (SD)**
including small motions	0.87 (±0.12)	2.2 (±0.9)	0.92 (±0.07)	1.7 (±0.08)
excluding small motions	0.91 (±0.06)	2.2 (±0.9)	0.93 (±0.05)	1.6 (±0.08)

The results show an improvement of the mean correlation for uncut data from 0.87 to 0.92 and for cut data from 0.91 to 0.93. Also, the standard deviations of angle difference get smaller by 0.5 resp. 0.6°.

Figure 28 shows an example (running with small steps) of marker-based, markerless and hybrid data of hip joint angles.

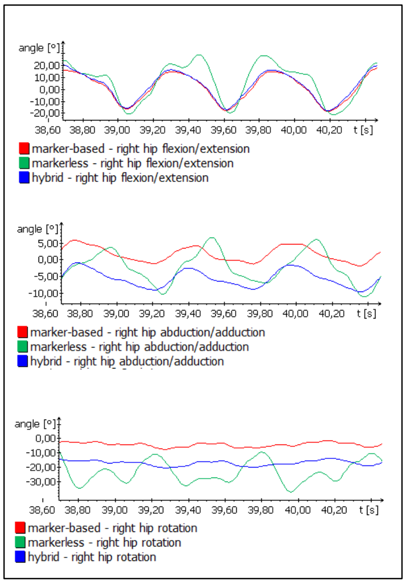

Figure 28: Marker-based, markerless and hybrid data of hip flexion/extension, abduction/adduction and rotation angles of running with small steps. Used hybrid combinations: spina right and left, mid spina markers (flexion/extension, abduction/adduction), additionally two knee markers and tracking with equally weighted marker and silhouette-correspondences for rotation movements.

Ankle

In Table 23, the results of hybrid tracking of ankle movements are presented.[85]

Table 23: Statistics of hybrid tracking of ankle movements with different marker combinations compared to marker-based tracking. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
ankle	plantar/dorsal flexion	forefoot	0.87 (±0.20)	5.1 (±2.2)
		forefoot, heel	0.93 (±0.12)	2.5 (±0.9)
	eversion/inversion	lat. ankle	0.26 (±0.36)	4.8 (±1.9)
		lat. and med. ankle	0.38 (±0.32)	3.7 (±1.4)
	abduction/adduction	lat. and med. knee	0.46 (±0.39)	8.6 (±7.0)
		lat. and med. knee, forefoot	0.55 (±0.36)	6.9 (±6.0)
		lat. and med. knee, forefoot, heel	0.49 (±0.38)	4.8 (±2.4)

Very good results (r = 0.93, SD of angle difference = 2.5°) are achieved for tracking of plantar/dorsal flexion movements with a forefoot and a heel marker. Results are a bit worse for tracking with only one forefoot marker (r = 0.87, SD of angle difference = 5.1°).

For tracking of eversion/inversion and abduction/adduction movements, no good results with all tested marker combinations are achieved.

Table 24: Statistics of hybrid tracking of ankle movements with different marker combinations compared to marker-based tracking excluding parts with small angle ranges. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
ankle	plantar/dorsal flexion	forefoot	0.90 (±0.11)	5.1 (±2.2)
		forefoot, heel	0.96 (±0.04)	2.5 (±0.9)
	eversion/inversion	lat. ankle	0.33 (±0.26)	4.4 (±1.8)
		lat. and med. ankle	0.38 (±0.33)	3.6 (±1.6)
	abduction/adduction	lat. and med. knee	0.45 (±0.41)	9.1 (±7.1)
		lat. and med. knee, forefoot	0.53 (±0.40)	6.6 (±5.9)
		lat. and med. knee, forefoot, heel	0.40 (±0.45)	4.8 (±2.8)

[85] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 74 - Table 76.

Table 24 shows the results for the same data excluding parts with small movements.[86] Mean values of correlation improve for plantar/dorsal flexion movements to 0.96 (forefoot and heel marker) and 0.90 (forefoot marker).

Figure 29 shows an example (running with big steps) of marker-based, markerless and hybrid data of ankle plantar/dorsal flexion angles.

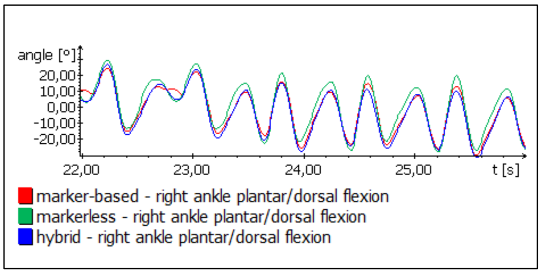

Figure 29: Marker-based, markerless and hybrid data of ankle plantar/dorsal flexion angles of running with big steps. Used hybrid combination: forefoot and heel markers.

Correlations for eversion/inversion and abduction/adduction motions excluding small movements are still bad. To examine if these problems are tracking problems or problems caused by the use of two different models, hybrid tracking data were compared to marker-based tracking data conducted in Simi Shape without using silhouette-correspondences. Table 25 shows the results of movements excluding parts with small angle ranges.[87]

Table 25: Statistics of hybrid tracking of ankle movements compared to full marker-based tracking in Shape excluding parts with small angle ranges. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
ankle	eversion/inversion	lat. ankle	0.53 (±0.30)	3.8 (±1.0)
		lat. and med. ankle	0.78 (±0.24)	2.3 (±0.9)
	abduction/adduction	lat. and med. knee	0.67 (±0.38)	6.0 (±4.8)
		lat. and med. knee, forefoot	0.73 (±0.31)	4.8 (±3.8)
		lat. and med. knee, forefoot, heel	0.91 (±0.05)	2.1 (±1.1)

For abduction/adduction movements, very high correlations and small standard deviation of angle difference are achieved using both knee markers, a forefoot and a heel marker.

[86] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 77 - Table 79.

[87] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 80 - Table 81.

For eversion/inversion movements, the best results are reached using both ankle markers. The mean correlation over all trials is 0.78, the mean value of standard deviation of angle difference is 2.3°. Looking at the angle ranges of motion (Table 80), it is obvious that most angle ranges of ankle eversion/inversion movements are small, often only slightly bigger than 5° and therefore close to be cut off. This is the reason why only a mean correlation of 0.78 is reached. Still, these results for both abduction/adduction and eversion/inversion movements are significantly better than those compared to marker-based data tracked with the Motion model.

Shoulder

The results of hybrid tracking of shoulder movements are presented in Table 26.[88]

Table 26: Statistics of hybrid tracking of shoulder movements with different marker combinations compared to marker-based tracking. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
shoulder	abduction/adduction	lat. elbow, triceps	0.90 (±0.11)	2.5 (±1.5)
	rotation	triceps	0.82 (±0.21)	8.1 (±6.0)
		lat. elbow, triceps	0.83 (±0.26)	4.0 (±3.5)

A mean correlation of 0.90 is reached for abduction/adduction movements tracked with a lat. elbow and a triceps marker. For shoulder rotation movements, the mean correlations are 0.82 for tracking with a triceps marker and 0.83 for tracking with a lat. elbow and a triceps marker.

Table 27: Statistics of hybrid tracking of shoulder movements with different marker combinations compared to marker-based tracking excluding parts with small angle ranges. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
shoulder	abduction/adduction	lat. elbow, triceps	0.94 (±0.05)	2.5 (±1.5)
	rotation	triceps	0.87 (±0.13)	8.5 (±6.2)
		lat. elbow, triceps	0.95 (±0.03)	4.9 (±4.1)

[88] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 82 - Table 83.

Table 27 shows the results without parts with small movements.[89] Values for abduction/adduction movements tracked with a lat. elbow and a triceps marker are very good (r = 0.94, SD of angle difference = 2.5°). For rotational movements, results tracked with the same marker combination turn out to be very good (r = 0.95, SD of angle difference = 4.9°). Tracking with only a triceps marker shows a correlation of r = 0.87 and a standard deviation of angle difference of 8.5°.

Figure 30 shows an example (jumping on the right leg) of marker-based, markerless and hybrid data of shoulder joint angles.

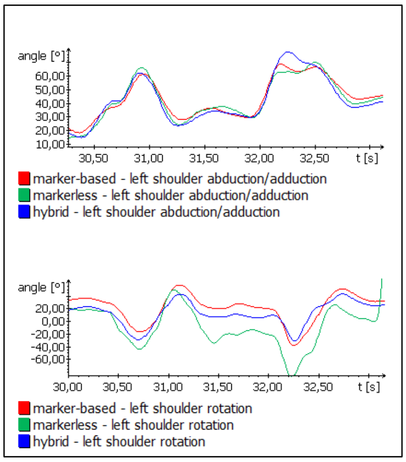

Figure 30: Marker-based, markerless and hybrid data of shoulder abduction/adduction and rotation angles of jumping on the right leg (full body marker set). Used hybrid combination: lat. elbow and triceps markers.

Elbow

Hybrid tracking results of elbow flexion/extension movements are presented in Table 28.[90]

[89] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 84 - Table 85.

[90] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 86.

Table 28: Statistics of hybrid tracking of shoulder movements with different marker combinations compared to marker-based tracking. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
elbow	flexion/extension	triceps	0.82 (±0.18)	5.3 (±3.8)
		lat. elbow, triceps	0.87 (±0.15)	4.2 (±2.5)
		lat. elbow, triceps, lat. and med. wrist	0.90 (±0.13)	4.0 (±2.3)

Mean correlations are 0.82 for tracking with a triceps marker, 0.87 for tracking with a triceps and a lat. elbow marker and 0.90 for using a triceps, a lat. elbow and two wrist markers. Standard deviations of angle difference are less than 5° for the two latter ones.

Table 29: Statistics of hybrid tracking of shoulder movements with different marker combinations compared to marker-based tracking excluding parts with small angle ranges. Presented are the mean values of correlation and standard deviation of angle difference as well as their standard deviations (indicated in brackets) over all complex trials.

Joint	Movement	Markers	MV correlation (SD)	MV SD angle diff. [°] (SD)
elbow	flexion/extension	triceps	0.87 (±0.08)	5.4 (±4.1)
		lat. elbow, triceps	0.92 (±0.07)	4.1 (±2.6)
		lat. elbow, triceps, lat. and med. wrist	0.94 (±0.07)	3.9 (±2.5)

For movements excluding parts with small ranges of motion (Table 29), the mean correlation improves for tracking with a triceps marker to 0.87, for tracking with a lat. elbow and a triceps marker to 0.92 and for the variant with four markers to 0.94 and a standard deviation of angle difference of 3.9°. Standard deviations of angle difference for the two latter ones are < 5°.[91]

Figure 31 shows an example (jumping on the left leg) of marker-based, markerless and hybrid data of elbow flexion/extension angles.

[91] More statistical values (angle ranges of Motion and Shape data, angle range differences, mean values of angle difference) can be seen in Appendix C.6, Table 87.

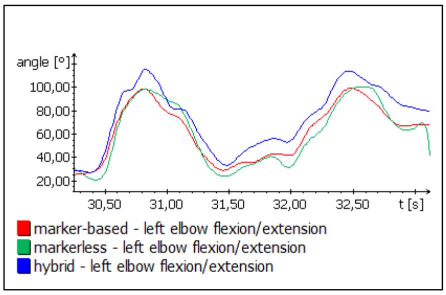

Figure 31: Marker-based, markerless and hybrid data of elbow flexion/extension angles of jumping on the left leg (full body marker set). Used hybrid combination: lat. elbow and triceps markers.

5 Summary and discussion

This chapter will provide a summary of previously presented results focussing on markerless tracking problems and which hybrid tracking marker sets are recommended to be used to get good tracking results for movements in all joints. Furthermore, a summary of factors that are not tracking-based and affect the results of comparing marker-based to markerless resp. hybrid tracking data is given as well as a critical reflection of this work. To conclude, the results of this study are compared to other studies that evaluate marker-based and markerless tracking.

5.1 Summary of markerless and hybrid tracking results of specific and complex movements

Table 30 shows a summarized comparison of markerless and hybrid tracked joint angle data of specific joint movements both evaluated against marker-based data. It also states the marker combinations that were used to get the presented good results.

Table 30: Correlations and standard deviations of angle difference of markerless and hybrid data vs. marker-based data for specific joint movements. First value of the right body side, second value of the left side. Markers are colorful appropriate to markers in Figure 32.

Joint	Movement	MARKERLESS		HYBRID		Markers
		Correlation	SD angle diff. [°]	Correlation	SD angle diff. [°]	
hip	flexion/ extension	0.86 / 0.91	14.5 / 18.6	1.00 / 0.99	2.0 / 3.2	spina right and left, mid spina
	abduction/ adduction	0.97 / 0.98	5.4 / 2.8	0.99 / 0.99	1.9 / 2.0	spina right and left, mid spina
	rotation	0.93 / 0.93	10.4 / 6.6	0.96 / 0.97	2.6 / 4.0	spina right and left, mid spina, lat. knee[92]
knee	flexion/ extension	1.00 / 1.00	3.3 / 4.5	very good markerless tracking		
ankle	plantar/dorsal flexion	0.98 / 0.96	3.9 / 5.5	0.98 / 0.98	3.7 / 3.8	forefoot[92]
	eversion/ inversion	0.39 / 0.81	5.5 / 4.1	0.94 / 0.91	2.1 / 3.7	lat. ankle[92]
	abduction/ adduction	0.58 / 0.90	7.9 / 5.6	0.92 / 0.96	5.0 / 3.1	lat. and med. knee[92]
shoulder	flexion/ extension	1.00 / 1.00	7.4 / 14.4	very good markerless tracking (high standard deviations of angle difference because of differently defined shoulder centers)		
	abduction/ adduction	0.88 / 0.78	9.9 / 13.3	0.93 / 0.95	7.6 / 5.6	lat. elbow, triceps
	rotation	0.90 / -0.10	14.5 / 24.6	0.99 / 1.00	1.6 / 3.1	triceps
elbow	flexion/ extension	1.00/ -0.99	5.9 / 106.4	0.99 / 0.99	4.5 / 7.1	triceps

Figure 32 depicts the full body marker set that is needed for inverse kinematic data calculation for marker-based tracking in Simi Motion (all spots). The markers that are needed for hybrid tracking of specific joint movements to get good results are highlighted in color.

[92] Slighty better results can be achieved by using marker combinations with one or two more markers. Results can be found in chapter 4.2.1. Since differences in correlations and standard deviations of angle difference are very small, the marker combinations with less markers are presented in this overview.

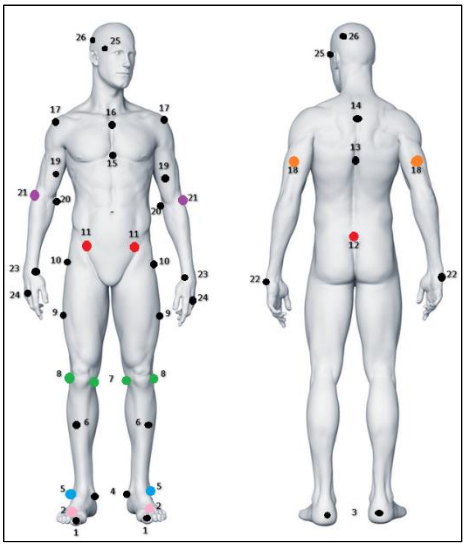

Figure 32: Marker setup of a full body markerset. Needed hybrid tracking markers for tracking of specific joint movements are highlighted.

For specific joint movements with big ranges of motion, very good markerless tracking results are reached for knee and shoulder flexion/extension movements. Still very good results are reached for ankle plantar/dorsal flexion and hip abduction/adduction movements but partly with standard deviations that are slightly higher than 5°. Hip rotational movements also show very high correlations but high standard deviations. All other joint movements have correlations of less than 0.9 for at least one body side and therefore should be supported by hybrid tracking. Using hybrid tracking for specific joint movements, very high correlations can be reached in every joint and every kind of movement. Also standard deviations are < 5° for all movements except of shoulder abduction/adduction and partly elbow flexion/extension motions.
All in all, 15 markers compared to a full body marker set for marker-based tracking with 37 markers (excluding hand and head markers) are needed for hybrid tracking of specific joint movements to get good results in all joint angles.

Table 31 shows a summarized comparison of markerless and hybrid tracked joint angle data of complex movements both evaluated against marker-based data. Parts with small angle ranges are excluded. It also states the marker combinations that were used to get the presented good results.

Table 31: Correlations and standard deviations of angle difference of markerless and hybrid data vs. marker-based data for complex movements excluding parts with small ranges of motion. Presented are the mean values and standard deviations over all trials and body sides. Marker labels are colorful appropriate to markers in Figure 33.

Joint	Movement	MARKERLESS		HYBRID		Markers
		MV correlation (SD)	MV SD angle diff. [°] (SD)	MV correlation (SD)	MV SD angle diff. [°] (SD)	
hip	flexion/ extension	0.82 (±0.21)	6.4 (±2.9)	0.99 (±0.02)	1.7 (±0.8)	spina right and left, mid spina
	abduction/ adduction	0.51 (±0.45)	4.6 (±1.5)	0.94 (±0.09)	1.2 (±0.7)	spina right and left, mid spina
	rotation	0.41 (±0.32)	9.2 (±3.8)	0.93 (±0.05)	1.6 (±0.8)	spina right and left, mid spina, med. and lat. knee
knee	flexion/ extension	0.98 (±0.03)	2.6 (±1.1)	very good markerless tracking		
ankle	plantar/dorsal flexion	0.91 (±0.08)	5.3 (±2.9)	0.96 (±0.04)	2.4 (±1.0)	forefoot, heel
	eversion/ inversion	0.26 (±0.42) / 0.42 (±0.36)[93]	5.0 (±2.4) / 5.0 (±2.3)[93]	0.38 (±0.33) / 0.78 (±0.24)[93]	3.6 (±1.6) / 2.3 (±0.9)[93]	lat. and med. ankle
	abduction/ adduction	0.34 (±0.42) / 0.65 (±0.34)[93]	7.2 (±3.9) / 5.1 (±3.1)[93]	0.40 (±0.45) / 0.91 (±0.05)[93]	4.8 (±2.8) / 2.1 (±1.1)[93]	lat. and med. knee, forefoot, heel
shoulder	flexion/ extension	0.96 (±0.02)	7.1 (±3.8)	very good markerless tracking (high standard deviations of angle difference because of differently defined shoulder centers)		
	abduction/ adduction	0.89 (±0.16)	2.8 (±1.2)	0.94 (±0.05)	2.5 (±1.5)	lat. elbow, triceps
	rotation	0.49 (±0.50)	39.1 (±51.9)	0.95 (±0.03)	4.9 (±4.1)	lat. elbow, triceps
elbow	flexion/ extension	0.42 (±0.70)	20.6 (±28.3)	0.92 (±0.07)	4.1 (±2.6)	lat. elbow, triceps[94]

Figure 33 shows again the full body marker set that is needed for inverse kinematic data calculation for marker-based tracking (all spots). The markers that are needed for hybrid tracking of complex movements to get good results are highlighted in color.

[93] Markerless and hybrid tracking results compared to full-marker-based tracking in Simi Shape without using silhouette-correspondences (the same model is used).

[94] Slighty better results can be achieved by additionally using a lat. and med. wrist marker. The mean value of correlation improves to 0.94 (see chapter 4.2.2).

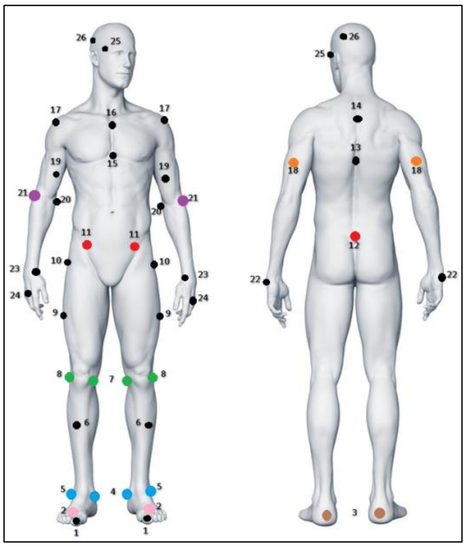

Figure 33: Marker setup of a full body markerset. Needed hybrid tracking markers for tracking of complex movements are highlighted.

For complex movements excluding parts with small ranges of motion, very good markerless tracking results are reached for knee and shoulder flexion/extension movements, which is similar to the results of specific joint movements. Also markerless tracking of ankle plantar/dorsal flexion movements is still very good, with a mean value of standard deviation of angle difference that is slightly higher than 5°. Very good hybrid tracking results using the presented marker combinations can be achieved for all joints and kinds of movements. Only ankle eversion/inversion and abduction/adduction movements do not show good results if data are compared to marker-based data tracked in Simi Motion because different models are used. Comparing results to full marker-based tracking in Shape without using silhouette-correspondences, but using the same model, results are good.

All in all, 19 markers compared to a full body marker set for marker-based tracking with 37 markers (excluding hand and head markers) are needed for hybrid tracking of complex movements to get good results in all joint angles.

5.2 Factors that lead to differences between markerless resp. hybrid and marker-based data

In the following, all factors that contribute do differences between markerless resp. hybrid tracking and marker-based tracking data are presented.

5.2.1 Markerless tracking problems and hybrid solutions to eliminate them

In the following, categories of problems that occur for markerless tracking are presented. Moreover, it is stated for which joint movements these problems especially occur and hybrid solutions to eliminate them are given.

Segments which are nearly rotationally symmetric

The pelvis is a kind of segment that is rather rotationally symmetric around all three axes. Thigh, shank, foot, upper arm and forearm are segments that are nearly rotationally symmetric around their local z-axes (thigh, shank, upper arm, forearm) or its local x-axis (foot). The problem for all these segments rotating around these axes is that the silhouette barely changes and therefore, these rotations cannot be tracked markerless. For hip and shoulder rotations, this problem only occurs for (nearly) straight knee and elbow joints since with bent knee and elbow joints, rotations of the arm resp. leg can be identified by the changing silhouette. The marker combinations that were tested in this study and provide good results can be found in Table 30 for specific joint movements and in Table 31 for complex movements. However, it is obvious that there are other spots to attach markers that support the tracking that were not tested in this study. Since markers were attached according to a predefined marker set so that data could be compared to marker-based tracking data for which it is necessary to place markers at exactly these predefined points, only these markers could be tested. However, the pelvis has to be stabilized by three markers that are not in line with each other. For the other segments, two markers are sufficient to get very good tracking results also for complex movements. The two markers have to be placed in a way that they are not located on the particular ‘critical’ rotational axis or on a line that is parallel to it. An optimal placement is in a way that the line that is defined by the markers is rectangular to the rotational axis. In this case, the rotation is unambiguously defined by the marker positions. For other marker placements, at least a small rotation is still possible if the model is not fitted 100 % accurately.

Also elbow flexion/extension angles are affected by the previously described kind of problem as the arm can strongly rotate in the shoulder joint using markerless tracking. As a consequence, the elbow movement that looks like a flexion is actually a hyperextension that is anatomically not possible. As mentioned before, this can only happen for a (nearly) stretched arm, meaning that the elbow is not bent. For all arm positions, one marker attached to the arm prevents these big rotations.

For the tracking of specific joint movements, only one attached marker, not two like it is needed for complex movements, turned out to be sufficient to get very good results for hip and shoulder rotations as well as ankle eversion/inversion movements. The reasons are explained in chapter 5.2.3.

Segments can slightly move within the silhouette

Small motions of the Shape model segments within the silhouette can happen because the model cannot be aligned to the silhouette so that they match for 100 %. This problem rather occurs for short segments (e.g. foot: plantar/dorsal flexion of the ankle joint) than for long segments (e.g. thigh: flexion/extension of the hip joint) and affects tracking results of movements with small ranges of motions more than those with big ranges of motion. Furthermore, segmentation problems can lead to this effect because due to these segmentation errors the silhouettes appear to be bigger than the body segments really are.
Bigger movements of segments within their silhouettes can occur if the size of the silhouette changes. This can happen because the morphsuit, which was used for most of the recordings, is not so close-fitting to all body parts. For instance, performing big shoulder abductions enlarges the size of the silhouette as the morphsuit is not close-fitting to the armpit. The same effect can occur for hip abduction/adduction movements since the morphsuit is not close-fitting to the crotch.
To eliminate this kind of problem, two markers that are not on a line parallel to the particular rotation axis have to be attached to the segment. Furthermore, performing movements without using a morphsuit should eliminate this problem.

Segments are covered by other parts of the body

The problem that segments can be covered by other body parts can especially occur for the arms. Figure 34 shows a situation in which the left forearm is hidden either by the upper body or by the upper arm or is lying in front of the body in all cameras. Only the camera in the right upper corner displays at least half of the forearm that is not covered. To calculate the forearm position, at least two cameras are necessary and therefore the left forearm is tracked wrong in this situation.

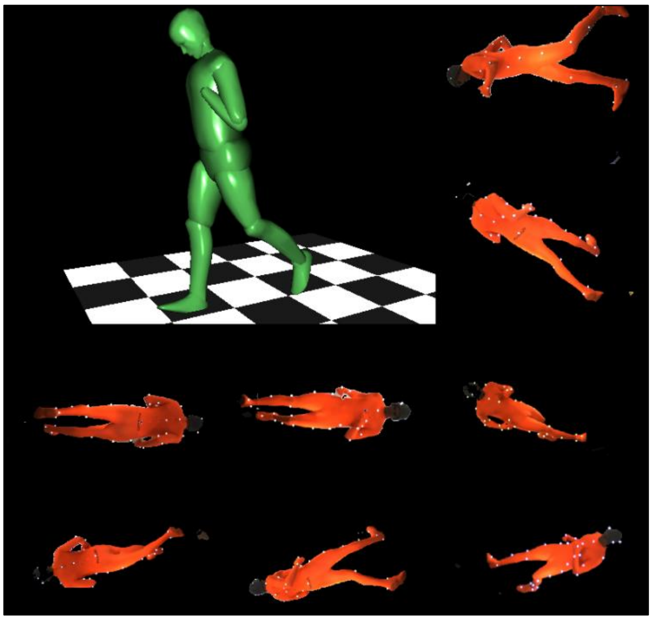

Figure 34: Shape tracking problem of the left forearm. The forearm is covered by the body in almost each camera.

This problem leads to incorrect elbow angles and can be prevented by attaching one markers to the forearm.

5.2.2 Factors that are no tracking problems but lead to differences between markerless resp. hybrid and marker-based joint angle data

The results presented in chapter 4.1.1.2 show that markerless data of small joint movements (< 5°) cannot be compared to marker-based data in this work. The reason is that the Shape model is always able to very slightly move within the silhouette as a 100 % accordance between model and silhouette is not reached. The pose of the Shape model during tracking is optimized for each frame which always means some kind of small movement of the model within the silhouette. These small movements highly affect correlations if angle ranges of the movement are small in general. If a different camera setup is used, e.g. cameras with a higher resolution, or if closer recordings of particular segments are made, the possibility of a better model fitting, and therefore obtaining better tracking results for small movements, is very likely.

Furthermore, the differently defined shoulder center in the Motion model compared to the Shape model affects differences between markerless resp. hybrid and marker-based tracking data. This factor influences shoulder flexion/extension and abduction/adduction angles as well as elbow flexion/extension angles.

Another factor is the knee joint that is built in different ways in the two models. In the Shape model, no abduction/adduction and rotation movements are possible in this joint. This affects ankle eversion/inversion and abduction/adduction movements.

These factors lead to differences between markerless and marker-based data that cannot be eliminated by using hybrid tracking variants.

5.2.3 Differences between tracking results of specific and complex movements

For some joints and kinds of movement, there are differences in the accuracy of tracking results between specific joint movements and complex movements. In the following, reasons for these differences are presented.
First of all, small tracking faults affect the recorded specific joint movements less than the complex movements since the ranges of motion are much higher. The mean value of all ranges of motion (of the marker-based data) is 80.3° compared to 37.2° of the complex movements. This also counts for each joint separately (see Appendices C.2 and C.3) and is therefore one reason for the better results of marker-based vs. markerless resp. hybrid tracking of specific movements compared to complex movements for each joint. Secondly, the specific joint movements were performed in a way that almost no other kind of movement was executed in the same joint. For example, during shoulder rotation movements nearly no flexion/extension or abduction/adduction shoulder movements were performed. As Cardan angles influence each other (faulty flexion/extension angles affect abduction/adduction angles, rotation angles are slightly affected by faulty flexion/extension or abduction/adduction angles) this source of error is prevented for specific joint movements but not for complex motions. Furthermore, only movements in the regarded joint were performed. For instance, for hip rotation movements, there were no movements in the knee or the ankle joints. Faulty trackings of other joint movements as they occur during complex movements can affect the regarded joint as these faults might be compensated by flawed motions in this joint. Nevertheless, for some joint movements, there are other factors that lead to differences. These are presented below.

Ankle eversion/inversion and abduction/adduction movements

In chapter 5.2.2, the reason for weak correlations between marker-based and markerless resp. hybrid tracked ankle eversion/inversion and abduction/adduction movements was explained. Looking at these angles of specific joint movements with big amplitudes, the correlations turn out to be very good with certain hybrid tracking variants (see chapter 4.2.1). The reason can be explained by the abduction/adduction and rotational movements of the knee of the Motion model during these specific ankle eversion/inversion and abduction/adduction movements (Figure 35).

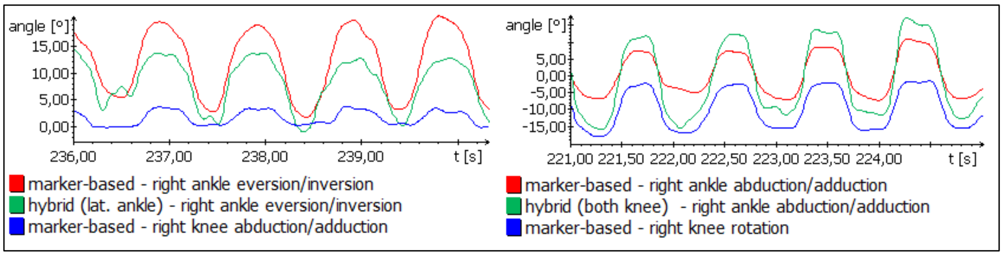

Figure 35: Left graphic: Ankle eversion/inversion angles of marker-based and hybrid tracking as well as marker-based knee abduction/adduction angles (right body side); Right graphic: Ankle abduction/adduction angles of marker-based and hybrid tracking as well as marker-based knee rotation angles (right body side).

The knee abduction/adduction movements are very consistent to the ankle eversion/inversion movements. The same situation can be seen regarding knee rotation movements compared to ankle abduction/adduction movements. Therefore, knee movements, which are only possible in the Motion model, do not influence correlations of marker-based against hybrid tracking in these cases of specific joint movements.

The results of hybrid tracking of ankle abduction/adduction movements that are presented in chapter 4.2.1 show better standard deviations of angle difference for tracking with both knee markers compared to tracking with both knee and two foot markers. The reason is explained in the following: The shank of the Motion model rotates in the same direction as the foot whereas the shank of the Shape model performs no rotation. Therefore, if the foot is tracked very precisely as it is in case of two foot markers, angle amplitudes are bigger for hybrid tracking with the Shape model than for marker-based tracking with the Motion model. For tracking with only two knee markers, the foot can slightly move within the silhouette and is therefore able to perform movements with smaller ranges of motion which leads to smaller angle amplitudes and consequently to smaller angle differences compared to the marker-based data, with slightly worse correlations though.

Elbow flexion/extension movements

For elbow flexion/extension angles, one source of error was figured out to be the forearm that can be covered by other parts of the body and therefore cannot be tracked accurately. This error source was eliminated for specific joint movements as the arms were stretched out away from the body.

5.3 Critical reflection of the work

Regarding the evaluated hybrid marker combinations for specific joint movements, it has to be considered that only two trials for each joint and kind of movement were analyzed. To validate these marker setups, more trials have to be done. However, for most sports or medical applications, complex movements are usually analyzed anyway. In this thesis, the evaluation of specific joint movements was mainly done as a first step in order to identify markerless tracking problems for each joint more clearly.

In the previous chapters, the focus was laid on identifying silhouette-based tracking problems. However, it has to be considered that there can also be faults in marker tracking data. Even though marker-data were checked carefully for mistakes, the possibility of minor tracking errors that influence marker data and consequently also correlations and standard deviations of angle difference between marker-based and markerless resp. hybrid data is given. Furthermore, incorrect marker placements can lead to incorrect calculated joint centers and coordinate systems which can also cause faults in marker data.

5.4 Markerless and hybrid tracking results compared to results of marker-based studies

In chapter 1.2.1, several studies about the accuracy of marker-based tracking by comparing tracking results conducted on the same day, on different days, by different examiner or comparing different marker placement protocols were presented (see Table 1). Figure 36 shows these results compared to the results that were obtained in this study. Since the correlation coefficient was analyzed in all studies, this value is presented in Figure 36. The red bars show the mean values of compared marker-based tracking results over all studies. The green bars present the mean correlations of markerless tracking and the blue bars those of hybrid tracking compared to marker-based tracking over all complex trials conducted in this study. Also, the standard deviations of correlations are displayed. Since no knee abduction/adduction and rotation movements were analyzed in this study, these joint movements are not presented as well as upper limb joint angles as these were not examined in the marker-based studies. The presented markerless and hybrid results of ankle eversion/inversion and abduction/adduction movements are those compared to marker-based tracking with the same used human model.

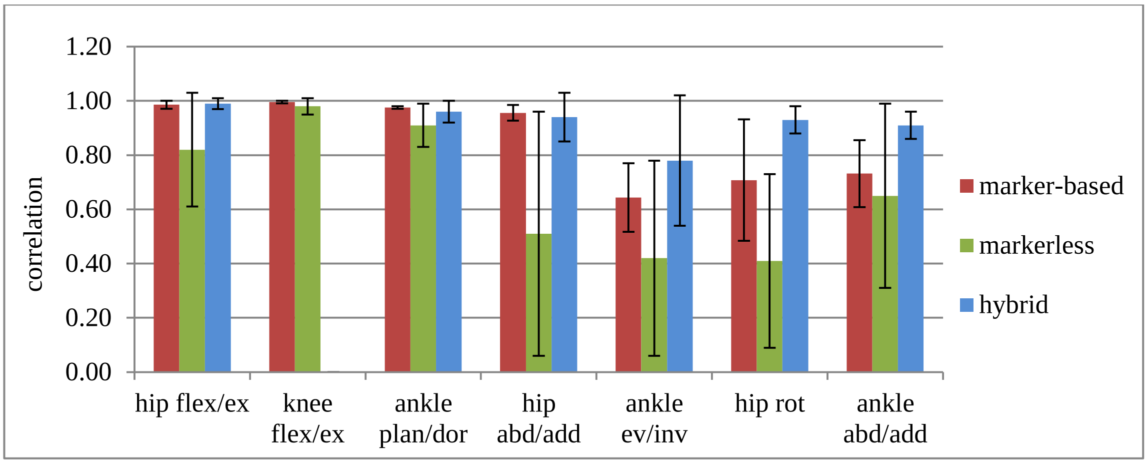

Figure 36: Markerless and hybrid data obtained in this study compared to results of marker-based studies. Presented are the mean values and standard deviations of correlations. Flex/ex: flexion/extension, plan/dor: plantar/dorsal flexion, abd/add: abduction/adduction, ev/inv: eversion/inversion, rot: rotation.

Knee flexion/extension angles of markerless and marker-based tracking show nearly the same very good results. Also, the mean correlation of ankle plantar/dorsal movements is only slightly worse for markerless tracking compared to marker-based studies, but with a significantly higher standard deviation. The same counts for ankle abduction/adduction motions. All other movements are considerably worse for markerless tracking. For hybrid tracking, all movements in sagittal plane as well as hip abduction/adduction movements are of about the same quality like marker-based results. All other out-of-sagittal plane movements present much better hybrid than marker-based results.

5.5 Markerless and hybrid tracking results compared to results of other markerless approaches

In chapter 1.2.2, studies that evaluate the accuracy of markerless tracking approaches were presented. Figure 37 shows these results compared to markerless and hybrid tracking results that were obtained in this study.[95] The mean values and standard deviations of angle deviations over all studies (red bars) resp. over all complex trials of this study (green and blue bars) are presented as angle deviations were analyzed in each of the studies, even though with slightly different methods. Results of knee and elbow movements in the frontal plane as well as knee, shoulder and elbow movements in the transversal plane are not shown as these joint angles were not examined either in this study or in none of the other studies presented in this work.

[95] Results of the study conducted by Choppin and Wheat (2012) are not included as the Microsoft Kinect tracking approach is not developed to provide a highly accurate markerless tracking.

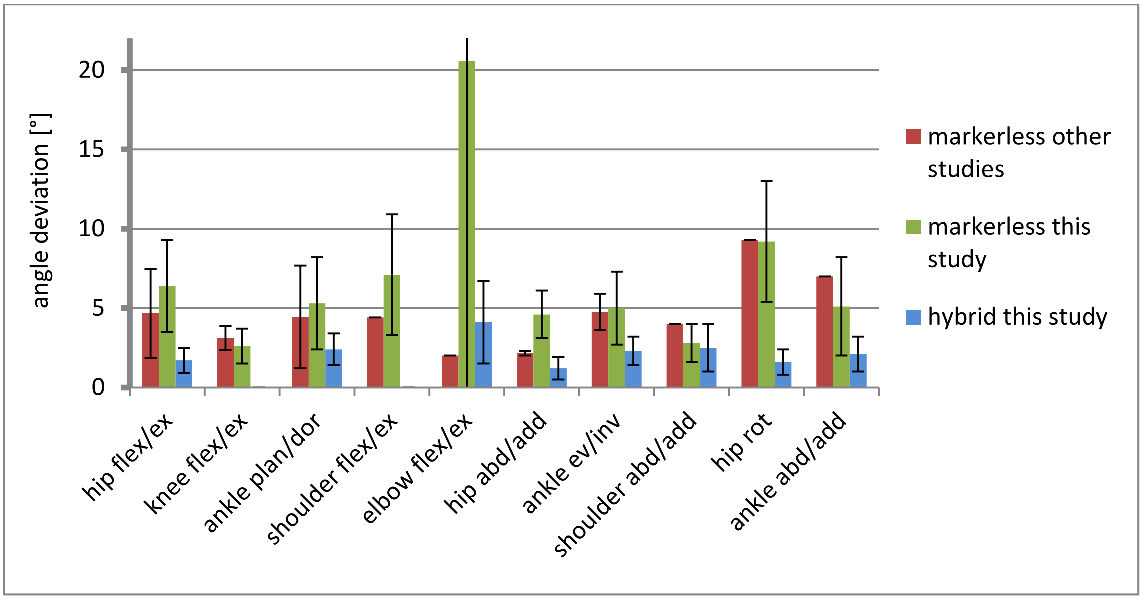

Figure 37: Markerless and hybrid data obtained in this study compared to results of other studies about markerless tracking approaches. Presented are the mean values and standard deviations of angle deviations. Flex/ex: flexion/extension, plan/dor: plantar/dorsal flexion, abd/add: abduction/adduction, ev/inv: eversion/inversion, rot: rotation.

Results of knee flexion/extension, ankle plantar/dorsal flexion and eversion/inversion movements, are very similar comparing markerless results of this study to other studies. Also, the mean angle deviation of hip rotation movements is nearly the same with a higher standard deviation in this study. As there is only one other study that examined the hip rotation angle, no standard deviation is presented here. For hip flexion/extension, shoulder flexion/extension and hip abduction/adduction movements, markerless tracking results obtained in this study are slightly worse than in other studies. On the contrary, results of shoulder and ankle abduction/adduction motions are a bit better in this work. Only the elbow joint shows much higher values in this study.[96] The reason is presented in chapter 5.2.1.

Regarding hybrid tracking results, all values are better than markerless tracking results obtained in other studies. The biggest approvement is found in movements in the transversal plane. An exception is the elbow flexion/extension angle that is a bit better in the one markerless study that examined this angle. However, both values are small.

[96] For a better representation, the very big standard deviation of elbow angle movements is not presented completely in the diagram.

6 Conclusion and outlook to further possibilities of investigation

In the beginning of this work, several advantageous aspects of markerless over marker-based tracking were mentioned. The aim of this study was to evaluate the accuracy of markerless tracking since this is a crucial factor in order for this technology to be used in medical and sports applications. The results show that all joint movements can be tracked very accurately either with markerless or with hybrid tracking. A comparison of the results obtained in this study to other studies that evaluate the accuracy of marker-based tracking shows that for some movements equally good results are achieved with markerless tracking (especially for knee flexion/extension movements). Using hybrid tracking, in all joint angles, the results are as least as good as the results of marker-based comparisons. In some out-of-sagittal plane movements, the results are even significantly better for hybrid tracking. Comparing the results of this study to other markerless approaches, the angle deviations have about the same dimensions for most joint angles. Using hybrid tracking, the deviations can be reduced significantly, especially for movements in the transversal plane.

Whether to apply markerless or hybrid tracking, and with which markers, should be chosen depending on the particular application and the needed accuracy for particular joint movements. Even if high accuracy in all joint movements is supposed to be gained, there is still a considerable saving of time as far less markers have to be attached compared to markers needed for marker-based tracking. Moreover, markers do not have to be accurately attached to specific anatomical landmarks as they are not used to calculate joint centers and coordinate systems. Therefore, also no errors due to wrong marker placement can be committed. Furthermore, if several analyses of the same person are conducted, the human model only has to be properly scaled for the first analysis. For further measurements, the model is saved and used again. Therefore, results are likely to be very reliable and comparable even if analyses are conducted on several days or by different examiners. All in all, the applicability of markerless and hybrid tracking has been shown to be appropriate to be used in the future of motion capture for medical and sports purposes.

There are still many subjects for further investigations.

In this study, only markers placed according to a full body inverse kinematic or a lower body marker set were tested for hybrid tracking. It was already mentioned that also other marker placements are very likely to support silhouette-based tracking and bring good hybrid tracking results. Nevertheless, different marker placements should be tested in another study to confirm this assumption.

Furthermore, the usability of other features instead of markers should be tested. The features could be some kind of tape or just black spots that are painted on the morphsuit. Possibilities of image processing could be used to invert the colors in order to make the black spots white so that they can be tracked.

Another subject of investigation should be another camera setup. All recordings in this work were done with eight high speed cameras using the same recordings for obtaining data in Simi Motion and Simi Shape. Interesting questions for further investigations are how markerless and hybrid data accuracy changes if camera setups with less cameras (e.g. six or four cameras) and different cameras (e.g. GoPros or web cams) are used. Also a higher camera resolution should be tested as it is likely to produce a more precise silhouette and therefore to lead to better markerless tracking results.

Other studies should focus on segmentation and model adjustment. In this work, all markerless and hybrid trackings were performed with a tracking parameter of 10 ipf. The influence of different settings (e.g. 15 ipf) on data accuracy should be tested. Also the importance of a good segmentation and model fitting should be evaluated more closely.

The repeatability of tracking results should be assessed by analyzing movements of the same subject on different days using the same scaled human model.

Since the Simi Shape software is still quite new, it can be assumed that it will be strongly developed and improved in the future so that an even more precise tracking in all joint angles (also those that could not be evaluated in this work) is likely.

This study provides a methodology that can be used for further tests.

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Appendix

A Survey about marker placement

Detailed results of the survey about marker placement are presented in Table 32. Participants were asked how many markers they usually place, which marker set they use and how much time they need for marker placement.

Table 32: Results of the survey about marker placement.

Respondent	Number of markers	Placement	Time [min]
1	20	Hanavan marker set (full body)	10-15
2	27	Marker set for lower extremities	20-30
3	29	LAMB model (full body)	30
4	30	Helen Hayes marker set + additional markers	15
5	40	Plug-in-Gait (full body)	10
6	40	Plug-in-Gait (full body)	10-15

B Data filtering and export

B.1 Comparison of statistics of data filtered with different frequencies

Data of marker-based and markerless tracking were filtered with a 2nd order low pass filter and a cut-off frequency of 6 and 10 Hz. Jumping movements on both legs with a full body marker set were analyzed. Correlations and standard deviations of angle difference comparing marker-based and markerless data were calculated. The differences between data filtered with 6 and 10 Hz were calculated (Table 33).

Table 33: Deviations of correlation and standard deviation of angle difference of data filtered with 6 and 10 Hz.

Joint	Movement	Deviation of correlation	Deviation of SD angle difference [°]
hip right	flexion/extension	0.00	0.1
	abduction/adduction	0.01	0.0
	rotation	0.02	0.1
knee right	flexion/extension	0.00	0.1
ankle right	plantar/dorsal flexion	0.00	0.1
	eversion/inversion	0.02	0.0
	abduction/adduction	0.01	0.1
hip left	flexion/extension	0.00	0.1
	abduction/adduction	0.01	0.0
	rotation	0.00	0.1
knee left	flexion/extension	0.00	0.0
ankle left	plantar/dorsal flexion	0.00	0.1
	eversion/inversion	0.02	0.1
	abduction/adduction	0.00	0.0
shoulder right	flexion/extension	0.00	0.0
	abduction/adduction	0.00	0.0
	rotation	0.01	0.1
elbow right	flexion/extension	0.00	0.0
shoulder left	flexion/extension	0.00	0.0
	abduction/adduction	0.00	0.0
	rotation	0.01	0.1
elbow left	flexion/extension	0.00	0.1

B.2 Data export

In order to allow a fast data processing, an Excel file was created to automatically calculate all statistical values (angle ranges of Motion and Shape data, angle range differences, mean values and standard deviations of angle difference). There are different files for all joints of the whole body, all joints of the lower body and for individual joints. In order to match the Excel file, the local joint angles have to be exported in a specific order: ankle right, knee right, hip right, ankle left, knee left, hip left (Motion data), ankle right, knee right, hip right, ankle left, knee left, hip left (Shape data), wrist right, elbow right, shoulder right, wrist left, elbow left, shoulder left (Motion data), wrist right, elbow right, shoulder right, wrist left, elbow left, shoulder left (Shape data). If only lower body joints are analyzed, only these data have to be exported. The same counts for analyzation of single joints. The data of the part of the recording that is supposed to be analyzed is cut out and pasted into the Excel template (first table). The template is built for data rows with a maximum of 1000 frames. If less frames are analyzed, zero rows have to be deleted (second table). In the third table, all statistical values are displayed.

C Detailed statistical results

In this appendix detailed statistical results will be presented. For appendices C2 to C6, correlation coefficients, angle ranges of Motion and Shape data, angle range differences between Motion and Shape data, mean values of angle difference and standard deviations of angle difference are presented. Negative values of angle range differences indicate a bigger angle range of Shape data compared to Motion data. Negative mean values of angle difference indicate a higher angle mean value of Shape data.

C.1 Test for normal distribution

Data were tested for normal distribution using Shapiro-Wilk test (Table 34 and Table 35). Presented are the significance values. They present the error probability of rejecting the null hypothesis that the data are normally distributed.[97]

[97] F. Brosius. 2013. SPSS 21. mitp, p. 405.

Table 34: Marker-based data tested for normal distribution using Shapiro-Wilk test. Presented are the significance values.

Motion data		**biking**	**lower marker jumps**				**jumping jack**	**full marker jumps**			**kicks and box punches**	**running**	
			both legs	**left leg**	**right leg**	**alternating legs**		**both legs**	**left leg**	**right leg**		**big steps**	**small steps**
hip right	flexion/extension	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
	rotation	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
knee right	flexion/extension	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ankle right	plantar/dorsal flexion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	eversion/inversion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00
hip left	flexion/extension	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	rotation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
knee left	flexion/extension	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ankle left	plantar/dorsal flexion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	eversion/inversion	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.00	0.00	0.00
shoulder right	flexion/extension	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
	rotation	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
elbow right	flexion/extension	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
shoulder left	flexion/extension	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
	rotation	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
elbow left	flexion/extension	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00

Table 35: Markerless data tested for normal distribution using Shapiro-Wilk test. Presented are the significance values.

Shape data		**biking**	**lower marker jumps**				**jumping jack**	**full marker jumps**			**kicks and box punches**	**running**	
			both legs	**left leg**	**right leg**	**alternating legs**		**both legs**	**left leg**	**right leg**		**big steps**	**small steps**
hip right	flexion/extension	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.01
	rotation	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
knee right	flexion/extension	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ankle right	plantar/dorsal flexion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	eversion/inversion	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
hip left	flexion/extension	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	rotation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
knee left	flexion/extension	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ankle left	plantar/dorsal flexion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	eversion/inversion	0.00	0.01	0.18	0.00	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
shoulder right	flexion/extension	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.03
	abduction/adduction	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
	rotation	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
elbow right	flexion/extension	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.05
shoulder left	flexion/extension	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
	abduction/adduction	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
	rotation	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00
elbow left	flexion/extension	0.00	-	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00

C.2 Statistics of markerless vs. marker-based data of specific joint movements

Table 36: Statistics of specific joint movements with big ranges of motion: Markerless data compared to marker-based data.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/ extension	0.86	86.3	89.1	-2.7	-2.2	14.5
hip left		0.91	93.3	62.1	31.1	-15.1	18.5
hip right	abduction/ adduction	0.97	54.1	41.5	12.6	-12.7	5.4
hip left		0.98	54.2	61.6	-7.4	-3.1	2.8
hip right	rotation	0.93	49.4	91.7	-42.4	9.3	10.4
hip left		0.93	58.3	63.3	-5.0	1.4	6.6
knee right	flexion/ extension	1.00	115.2	124.4	-9.3	1.0	3.3
knee left		1.00	130.7	137.1	-6.4	5.6	4.5
ankle right	plantar-/dorsal flexion	0.98	65.9	59.5	6.4	0.6	3.9
ankle left		0.96	65.6	56.2	9.3	2.9	5.5
ankle right	eversion/ inversion	0.39	18.7	7.2	11.5	2.9	5.5
ankle left		0.81	16.1	7.0	9.2	-5.9	4.0
ankle right	abduction/ adduction	0.58	18.3	40.9	-22.7	19.6	7.9
ankle left		0.90	28.0	41.6	-13.6	14.7	5.6
shoulder right	flexion/ extension	1.00	147.7	163.6	-15.9	3.7	7.4
shoulder left		1.00	187.7	223.7	-36.0	8.6	14.4
shoulder right	abduction/ adduction	0.88	84.6	77.5	7.0	-1.7	9.8
shoulder left		0.78	79.7	68.7	11.0	11.1	13.3
shoulder right	rotation	0.90	52.5	102.5	-49.9	40.8	14.5
shoulder left		-0.10	73.8	32.6	41.2	-225.1	24.6
elbow right	flexion/ extension	1.00	134.1	149.7	-15.5	3.7	5.8
elbow left		-0.99	151.7	155.7	-4.0	167.3	106.4

Table 37: Statistics of specific joint movements with small ranges of motion: Markerless data compared to marker-based data.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/ extension	0.17	4.97	15.19	-10.22	9.33	3.11
hip left		-0.24	4.24	11.26	-7.02	-8.38	2.86
hip right	abduction/ adduction	0.13	2.36	8.33	-5.97	-4.86	1.62
hip left		0.60	1.24	9.43	-8.19	-8.08	2.19
hip right	rotation	0.10	2.65	10.23	-7.58	0.60	1.99
hip left		0.24	2.16	13.73	-11.56	3.74	4.14
knee right	flexion/ extension	0.33	0.98	4.30	-3.32	-13.47	0.81
knee left		0.38	2.01	3.60	-1.59	4.91	0.76
ankle right	plantar-/dorsal flexion	0.17	3.95	7.46	-3.51	7.43	1.52
ankle left		0.15	4.20	5.47	-1.26	6.03	1.92
ankle right	eversion/ inversion	0.02	1.93	16.53	-14.60	4.75	3.41
ankle left		0.32	4.00	6.41	-2.41	-9.75	1.26
ankle right	abduction/ adduction	0.04	1.99	13.04	-11.05	-7.64	1.92
ankle left		0.31	4.61	18.73	-14.12	3.59	3.10
shoulder right	flexion/ extension	0.49	3.66	9.21	-5.55	4.56	1.34
shoulder left		0.73	4.23	7.98	-3.75	-2.79	1.80
shoulder right	abduction/ adduction	0.33	2.85	3.73	-0.88	-11.87	0.95
shoulder left		0.11	2.85	4.99	-2.13	10.09	1.19
shoulder right	rotation	0.37	3.23	17.86	-14.62	38.83	3.78
shoulder left		-0.17	4.31	23.14	-18.82	-219.36	7.90
elbow right	flexion/ extension	0.25	2.66	5.52	-2.86	9.01	1.40
elbow left		-0.16	2.10	4.12	-2.02	23.97	1.03

C.3 Statistics of markerless vs. marker-based data of complex movements – including parts with small ranges of motion

Table 38: Statistics of biking: Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.96	38.6	46.1	-7.5	7.7	3.5
	abduction/adduction	0.81	7.3	11.2	-3.9	-2.4	1.7
	rotation	0.58	7.7	34.0	-26.3	31.3	10.4
knee right	flexion/extension	1.00	57.5	63.1	-5.6	-9.3	2.5
ankle right	plantar/dorsal flexion	0.99	42.7	61.0	-18.4	4.4	6.0
	eversion/inversion	-0.65	8.9	15.9	-7.0	23.8	7.0
	abduction/adduction	0.71	15.3	18.7	-3.4	0.6	3.7
hip left	flexion/extension	0.91	37.9	44.0	-6.1	-1.6	3.4
	abduction/adduction	0.97	5.5	26.1	-20.7	-2.4	7.1
	rotation	0.64	6.3	29.2	-22.8	13.0	10.0
knee left	flexion/extension	1.00	58.7	62.3	-3.6	-0.7	1.2
ankle left	plantar/dorsal flexion	0.80	14.0	28.3	-14.3	-1.7	6.3
	eversion/inversion	-0.22	4.5	8.4	-3.9	15.8	2.9
	abduction/adduction	-0.48	16.0	14.5	1.5	-7.6	5.9
shoulder right	flexion/extension	0.80	5.8	4.4	1.4	-20.8	1.2
	abduction/adduction	0.70	2.1	6.1	-4.0	7.1	1.2
	rotation	0.86	3.1	22.5	-19.4	123.8	5.6
elbow right	flexion/extension	-0.70	8.0	13.0	-5.0	49.1	5.6
shoulder left	flexion/extension	0.42	4.9	1.9	2.9	-13.0	1.2
	abduction/adduction	0.61	4.5	4.2	0.2	-3.5	1.0
	rotation	0.01	6.1	7.2	-1.1	29.7	2.5
elbow left	flexion/extension	0.31	3.6	4.5	-0.9	9.2	1.1

Table 39: Statistics of jumping on both legs (lower extremities marker set): Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.21	20.7	14.7	6.0	38.8	6.0
	abduction/adduction	-0.47	3.9	19.2	-15.3	-1.0	5.8
	rotation	0.12	7.7	66.6	-58.9	19.0	15.1
knee right	flexion/extension	0.98	46.3	40.3	6.0	-2.8	2.7
ankle right	plantar/dorsal flexion	0.94	49.1	62.2	-13.1	5.6	6.5
	eversion/inversion	0.64	21.7	13.9	7.8	-0.9	5.1
	abduction/adduction	0.54	9.4	48.8	-39.5	0.8	10.5
hip left	flexion/extension	0.89	23.5	15.5	8.0	31.1	3.1
	abduction/adduction	0.53	4.1	22.0	-17.9	-1.2	5.8
	rotation	0.16	8.2	43.5	-35.3	-5.6	12.1
knee left	flexion/extension	1.00	48.2	48.0	0.2	4.3	1.7
ankle left	plantar/dorsal flexion	0.98	54.5	54.0	0.6	1.7	4.0
	eversion/inversion	0.60	17.1	9.1	8.1	-10.1	3.0
	abduction/adduction	0.68	13.1	24.8	-11.7	-15.4	4.2

Table 40: Statistics of jumping on the left leg (lower extremities marker set): Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.74	7.2	10.5	-3.3	37.2	1.5
	abduction/adduction	0.71	5.6	12.8	-7.1	-6.4	2.4
	rotation	-0.07	8.3	24.9	-16.7	15.0	5.7
knee right	flexion/extension	0.97	11.4	14.7	-3.3	-0.4	1.2
ankle right	plantar/dorsal flexion	0.21	5.3	28.7	-23.4	-0.9	8.4
	eversion/inversion	0.06	3.2	19.3	-16.1	21.7	5.8
	abduction/adduction	0.02	2.2	25.6	-23.4	15.9	6.5
hip left	flexion/extension	0.93	14.9	27.0	-12.1	32.2	3.5
	abduction/adduction	0.86	9.3	18.7	-9.5	-9.1	2.7
	rotation	0.25	8.1	64.0	-55.9	-12.2	17.3
knee left	flexion/extension	0.99	36.6	47.7	-11.0	5.0	3.1
ankle left	plantar/dorsal flexion	0.95	51.5	46.8	4.7	-6.3	4.3
	eversion/inversion	-0.20	12.8	24.5	-11.7	-30.3	7.2
	abduction/adduction	0.34	13.3	32.9	-19.6	-1.7	7.7

Table 41: Statistics of jumping on the right leg (lower extremities marker set): Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.71	27.1	15.1	12.0	34.8	3.3
	abduction/adduction	0.96	8.2	17.1	-8.9	2.3	2.6
	rotation	0.43	19.4	30.6	-11.1	-4.5	8.3
knee right	flexion/extension	0.99	35.2	38.9	-3.7	-1.3	1.9
ankle right	plantar/dorsal flexion	0.96	47.5	48.9	-1.4	1.3	3.5
	eversion/inversion	0.67	24.4	14.3	10.1	-1.2	5.3
	abduction/adduction	0.57	11.1	15.2	-4.1	4.2	3.5
hip left	flexion/extension	0.00	4.5	8.1	-3.6	27.9	2.8
	abduction/adduction	0.61	2.8	11.1	-8.3	2.5	2.5
	rotation	0.49	10.1	20.3	-10.3	-12.5	4.3
knee left	flexion/extension	0.78	7.8	8.2	-0.5	5.2	1.3
ankle left	plantar/dorsal flexion	0.53	6.0	37.2	-31.2	-6.6	9.6
	eversion/inversion	-0.20	3.5	40.5	-37.0	-14.3	10.5
	abduction/adduction	-0.01	1.4	17.3	-15.9	-28.9	4.2

Table 42: Statistics of jumping on alternating legs (lower extremities marker set): Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.79	13.0	25.0	-12.0	34.5	3.6
	abduction/adduction	0.39	9.0	25.8	-16.8	-1.2	5.9
	rotation	0.67	15.8	39.7	-23.9	15.2	7.0
knee right	flexion/extension	1.00	81.4	87.5	-6.0	1.0	1.8
ankle right	plantar/dorsal flexion	0.92	37.9	43.3	-5.5	1.2	4.0
	eversion/inversion	0.26	23.1	29.3	-6.2	6.5	10.3
	abduction/adduction	-0.17	10.7	27.0	-16.4	6.7	8.1
hip left	flexion/extension	0.97	20.7	36.4	-15.7	27.9	4.8
	abduction/adduction	0.12	13.6	22.6	-9.0	-1.5	6.7
	rotation	0.52	20.8	61.8	-41.0	-9.8	8.9
knee left	flexion/extension	0.99	83.7	92.7	-9.1	7.6	3.6
ankle left	plantar/dorsal flexion	0.97	57.2	51.4	5.8	-1.7	3.3
	eversion/inversion	0.55	18.7	30.8	-12.1	-17.1	9.2
	abduction/adduction	-0.53	20.3	51.0	-30.7	-16.3	13.2

Table 43: Statistics of jumping jack movements (lower extremities marker set): Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.31	27.6	43.6	-16.0	-24.6	10.4
	abduction/adduction	0.92	31.3	33.3	-2.0	-6.7	3.7
	rotation	0.33	24.6	40.8	-16.2	-0.9	10.3
knee right	flexion/extension	0.98	39.3	40.5	-1.2	7.5	2.0
ankle right	plantar/dorsal flexion	0.96	40.4	60.2	-19.8	-9.0	7.3
	eversion/inversion	0.29	38.4	14.9	23.4	-13.6	7.6
	abduction/adduction	0.40	14.0	34.6	-20.5	-2.5	6.4
hip left	flexion/extension	0.41	30.8	52.9	-22.1	-17.5	11.5
	abduction/adduction	0.91	26.2	39.0	-12.8	-1.9	4.1
	rotation	0.26	23.1	30.1	-6.9	23.5	7.6
knee left	flexion/extension	0.95	46.8	46.7	0.1	1.5	4.3
ankle left	plantar/dorsal flexion	0.94	47.6	60.8	-13.2	-6.7	6.1
	eversion/inversion	0.78	21.1	16.2	4.9	11.7	3.3
	abduction/adduction	0.13	8.8	49.5	-40.7	-14.3	10.5

Table 44: Statistics of jumping on both legs (full body marker set): Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.99	98.8	113.8	-15.0	3.0	5.3
	abduction/adduction	0.34	13.1	12.4	0.7	-0.9	4.1
	rotation	0.65	21.1	34.7	-13.6	18.0	6.2
knee right	flexion/extension	0.98	86.5	79.0	7.5	-2.1	3.1
ankle right	plantar/dorsal flexion	0.97	58.6	69.8	-11.2	4.1	4.5
	eversion/inversion	0.73	6.9	16.7	-9.8	7.6	2.6
	abduction/adduction	0.85	8.6	37.0	-28.3	0.6	5.9
hip left	flexion/extension	0.99	94.8	123.8	-29.0	-0.6	7.7
	abduction/adduction	0.46	14.7	16.1	-1.4	-8.2	4.5
	rotation	0.85	25.5	45.5	-20.1	-0.8	8.3
knee left	flexion/extension	1.00	79.2	86.7	-7.4	4.3	2.4
ankle left	plantar/dorsal flexion	0.99	61.8	72.7	-10.9	5.4	4.1
	eversion/inversion	0.25	6.5	17.2	-10.7	2.3	4.7
	abduction/adduction	0.89	14.5	18.1	-3.6	1.7	3.4

shoulder right	flexion/extension	0.97	90.1	103.4	-13.3	-4.0	4.1
	abduction/adduction	0.97	19.4	16.8	2.6	0.0	1.4
	rotation	0.89	58.5	87.8	-29.4	-13.9	12.6
elbow right	flexion/extension	0.91	66.7	70.1	-3.4	5.7	2.8
shoulder left	flexion/extension	0.97	82.6	104.0	-21.4	-3.8	5.6
	abduction/adduction	0.95	24.1	26.6	-2.5	1.1	2.6
	rotation	0.79	46.3	71.8	-25.5	18.0	11.0
elbow left	flexion/extension	0.85	87.8	99.5	-11.7	0.9	7.9

Table 45: Statistics of jumping on the left leg (full body marker set): Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.93	48.1	43.3	4.8	-6.7	6.4
	abduction/adduction	0.15	11.4	13.6	-2.3	-10.1	4.1
	rotation	0.34	16.4	25.3	-8.9	12.7	7.1
knee right	flexion/extension	0.96	21.0	17.5	3.5	1.9	1.9
ankle right	plantar/dorsal flexion	0.77	20.9	15.5	5.4	-1.2	3.0
	eversion/inversion	0.33	7.8	27.1	-19.3	21.2	6.5
	abduction/adduction	0.31	6.2	13.6	-7.3	16.5	3.0
hip left	flexion/extension	0.94	74.3	72.7	1.6	-2.9	7.1
	abduction/adduction	-0.05	16.8	11.6	5.2	-18.3	5.2
	rotation	0.38	17.8	45.7	-27.9	-7.2	9.2
knee left	flexion/extension	0.89	67.9	73.5	-5.6	5.6	3.5
ankle left	plantar/dorsal flexion	0.92	59.4	68.2	-8.8	2.4	4.8
	eversion/inversion	0.19	10.9	11.9	-0.9	-5.3	3.4
	abduction/adduction	0.39	12.5	29.5	-17.0	1.3	8.1
shoulder right	flexion/extension	0.97	74.3	99.8	-25.5	-14.9	6.9
	abduction/adduction	0.98	47.6	45.8	1.8	4.8	2.5
	rotation	-0.52	64.2	368.1	-303.8	57.3	140.6
elbow right	flexion/extension	-0.97	56.6	63.9	-7.3	110.1	32.6
shoulder left	flexion/extension	0.96	102.0	144.5	-42.6	-6.3	10.0
	abduction/adduction	0.97	50.4	55.2	-4.8	0.8	3.0
	rotation	0.91	94.7	138.5	-43.9	31.1	13.1
elbow left	flexion/extension	0.97	73.7	79.9	-6.2	1.7	6.0

Table 46: Statistics of jumping on the right leg (full body marker set): Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.96	63.6	75.3	-11.7	0.4	6.3
	abduction/adduction	0.69	18.7	23.8	-5.1	9.3	3.9
	rotation	0.54	23.9	30.1	-6.1	19.6	6.1
knee right	flexion/extension	0.99	70.7	73.2	-2.5	3.7	2.6
ankle right	plantar/dorsal flexion	0.90	52.9	69.0	-16.1	2.1	5.1
	eversion/inversion	-0.44	7.8	21.0	-13.2	15.6	5.6
	abduction/adduction	0.78	8.5	35.3	-26.8	2.9	6.4
hip left	flexion/extension	0.94	63.3	79.5	-16.2	-1.8	8.6
	abduction/adduction	-0.17	9.0	15.3	-6.3	2.2	5.0
	rotation	0.69	36.3	33.9	2.3	-4.0	7.5
knee left	flexion/extension	0.95	33.3	34.7	-1.4	5.3	2.6
ankle left	plantar/dorsal flexion	0.66	20.2	18.7	1.5	-2.5	3.9
	eversion/inversion	-0.22	20.7	16.1	4.5	-21.1	6.5
	abduction/adduction	-0.22	14.2	13.1	1.1	-10.4	4.8
shoulder right	flexion/extension	0.99	114.2	144.4	-30.2	-14.9	12.2
	abduction/adduction	0.93	32.7	38.1	-5.4	0.9	3.5
	rotation	-0.36	99.9	369.9	-270.0	21.8	152.0
elbow right	flexion/extension	-0.89	59.7	52.7	7.0	152.3	23.8
shoulder left	flexion/extension	0.95	53.5	72.6	-19.2	-9.8	6.8
	abduction/adduction	0.96	51.4	49.9	1.6	0.3	3.0
	rotation	0.91	54.0	54.5	-0.6	16.4	4.9
elbow left	flexion/extension	0.90	72.4	88.3	-15.9	2.3	6.5

Table 47: Statistics of kicks and box punches: Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.85	105.7	148.8	-43.1	5.9	11.8
	abduction/adduction	0.55	54.1	76.7	-22.6	7.3	7.2
	rotation	0.26	36.3	92.3	-56.0	32.4	17.1
knee right	flexion/extension	0.92	133.3	124.7	8.6	-1.1	5.3
ankle right	plantar/dorsal flexion	0.75	81.6	99.4	-17.8	-1.6	8.1
	eversion/inversion	0.51	23.6	43.8	-20.2	15.8	8.4
	abduction/adduction	0.13	30.4	60.7	-30.2	-5.0	14.4

hip left	flexion/extension	0.85	69.5	80.1	-10.7	2.8	11.8
	abduction/adduction	0.80	49.7	78.6	-28.9	-0.4	7.7
	rotation	0.66	56.6	107.3	-50.7	-13.3	14.6
knee left	flexion/extension	0.93	90.3	94.5	-4.3	1.5	4.8
ankle left	plantar/dorsal flexion	0.74	46.1	86.3	-40.2	3.4	8.3
	eversion/inversion	0.38	32.5	35.4	-2.9	-1.3	7.6
	abduction/adduction	0.21	23.5	78.4	-54.9	9.3	14.0
shoulder right	flexion/extension	0.94	152.4	179.1	-26.8	0.7	13.9
	abduction/adduction	0.85	85.4	83.2	2.2	-0.3	5.7
	rotation	0.43	144.8	373.9	-229.0	13.1	79.9
elbow right	flexion/extension	0.49	113.8	269.7	-155.9	40.1	84.2
shoulder left	flexion/extension	0.93	109.2	148.8	-39.6	-3.1	12.2
	abduction/adduction	0.97	101.2	90.6	10.6	-1.2	3.8
	rotation	0.80	113.3	308.8	-195.5	26.1	28.2
elbow left	flexion/extension	0.54	115.7	362.8	-247.1	22.0	78.7

Table 48: Statistics of running with big steps: Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.94	42.3	51.1	-8.8	3.8	6.6
	abduction/adduction	0.59	10.8	21.4	-10.6	2.5	3.9
	rotation	0.55	11.9	36.5	-24.6	19.7	8.2
knee right	flexion/extension	1.00	83.3	85.8	-2.5	-4.4	1.9
ankle right	plantar/dorsal flexion	0.94	46.3	47.6	-1.3	3.5	4.0
	eversion/inversion	0.40	14.0	18.9	-4.9	10.4	3.4
	abduction/adduction	0.41	13.7	36.2	-22.4	-2.6	10.2
hip left	flexion/extension	0.88	42.4	48.1	-5.7	1.2	6.3
	abduction/adduction	0.81	12.8	27.6	-14.8	-2.4	4.9
	rotation	0.78	16.3	36.2	-19.9	-8.2	6.1
knee left	flexion/extension	1.00	79.6	82.9	-3.3	-0.6	2.0
ankle left	plantar/dorsal flexion	0.96	54.8	57.4	-2.7	-2.6	3.8
	eversion/inversion	0.31	10.8	29.0	-18.3	-11.5	7.1
	abduction/adduction	-0.04	15.2	40.9	-25.6	3.2	10.8

shoulder right	flexion/extension	0.98	37.8	45.1	-7.3	8.6	3.1
	abduction/adduction	0.98	26.0	30.5	-4.5	0.0	2.3
	rotation	0.91	27.1	34.7	-7.6	-21.6	4.1
elbow right	flexion/extension	0.94	31.5	33.2	-1.7	-13.2	2.4
shoulder left	flexion/extension	0.97	39.6	53.6	-14.0	11.5	3.5
	abduction/adduction	0.38	10.9	9.9	1.0	1.0	2.1
	rotation	0.47	20.2	27.9	-7.7	36.5	7.2
elbow left	flexion/extension	0.70	17.7	24.7	-6.9	-5.6	4.2

Table 49: Statistics of running with small steps: Markerless data compared to marker-based data including parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.86	36.1	50.5	-14.4	-5.3	7.5
	abduction/adduction	0.57	7.8	17.8	-10.0	3.9	4.0
	rotation	-0.31	6.2	27.6	-21.4	19.1	8.2
knee right	flexion/extension	1.00	58.4	64.2	-5.8	-4.1	2.1
ankle right	plantar/dorsal flexion	0.87	20.7	25.3	-4.6	4.4	4.0
	eversion/inversion	0.43	10.4	12.8	-2.5	9.4	3.4
	abduction/adduction	0.45	6.3	32.7	-26.4	-2.6	9.5
hip left	flexion/extension	0.80	35.0	44.4	-9.3	-9.3	7.8
	abduction/adduction	0.75	7.8	18.5	-10.6	-2.6	3.8
	rotation	0.54	7.9	23.1	-15.2	-2.3	5.5
knee left	flexion/extension	1.00	59.6	65.3	-5.7	1.4	1.8
ankle left	plantar/dorsal flexion	0.98	19.6	26.2	-6.6	-2.4	2.3
	eversion/inversion	0.28	8.1	23.9	-15.9	-11.1	6.4
	abduction/adduction	0.28	5.6	29.8	-24.2	-2.7	8.7
shoulder right	flexion/extension	0.92	28.4	22.4	6.0	15.0	3.6
	abduction/adduction	0.94	14.9	16.5	-1.6	-1.5	1.2
	rotation	0.64	15.6	13.4	2.1	-18.7	3.9
elbow right	flexion/extension	0.95	33.8	32.7	1.2	-16.6	2.5
shoulder left	flexion/extension	0.94	38.8	45.7	-6.9	10.2	3.6
	abduction/adduction	0.84	12.3	13.6	-1.3	0.6	1.7
	rotation	-0.05	14.7	33.1	-18.4	48.3	11.5
elbow left	flexion/extension	0.75	21.8	34.0	-12.2	-7.4	4.4

C.4 Statistics of markerless vs. marker-based data of complex movements – excluding parts with small ranges of motion

Table 50: Statistics of biking: Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.96	38.6	46.1	-7.5	7.7	3.5
	abduction/adduction	entire part has to be cut off					
	rotation	entire part has to be cut off					
knee right	flexion/extension	1.00	57.5	63.1	-5.6	-9.3	2.5
ankle right	plantar/dorsal flexion	0.99	42.7	61.0	-18.4	4.4	6.0
	eversion/inversion	-0.09	5.3	4.4	0.9	23.6	2.0
	abduction/adduction	1.00	10.5	7.3	3.1	-2.4	1.7
hip left	flexion/extension	0.91	37.9	44.0	-6.1	-1.6	3.4
	abduction/adduction	0.97	5.5	26.1	-20.7	-2.4	7.1
	rotation	entire part has to be cut off					
knee left	flexion/extension	1.00	58.7	62.3	-3.6	-0.7	1.2
ankle left	plantar/dorsal flexion	0.82	5.1	7.7	-2.6	3.6	1.6
	eversion/inversion	entire part hast o be cut off					
	abduction/adduction	-0.62	16.0	10.7	5.3	-10.2	7.3
shoulder right	flexion/extension	entire part has to be cut off					
	abduction/adduction	entire part has to be cut off					
	rotation	entire part has to be cut off					
elbow right	flexion/extension	-0.61	5.9	8.6	-2.7	52.0	4.6
shoulder left	flexion/extension	entire part has to be cut off					
	abduction/adduction	entire part has to be cut off					
	rotation	entire part has to be cut off					
elbow left	flexion/extension	entire part has to be cut off					

Table 51: Statistics of jumping on both legs (lower extremities marker set): Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.21	20.7	14.7	6.0	38.8	6.0
	abduction/adduction	entire part has to be cut off					
	rotation	0.12	7.7	67.5	-59.8	19.0	15.1
knee right	flexion/extension	0.98	46.3	40.3	6.0	-2.8	2.7
ankle right	plantar/dorsal flexion	0.94	49.1	62.2	-13.1	5.6	6.5
	eversion/inversion	0.64	21.7	13.9	7.8	-0.9	5.1
	abduction/adduction	0.54	9.4	48.8	-39.5	0.8	10.5
hip left	flexion/extension	0.89	23.5	15.5	8.0	31.1	3.1
	abduction/adduction	entire part has to be cut off					
	rotation	0.16	8.2	43.5	-35.3	-5.6	12.1
knee left	flexion/extension	1.00	48.2	48.0	0.2	4.3	1.7
ankle left	plantar/dorsal flexion	0.98	54.5	54.0	0.6	1.7	4.0
	eversion/inversion	0.60	17.1	9.1	8.1	-10.1	3.0
	abduction/adduction	0.68	13.1	24.8	-11.7	-15.4	4.2

Table 52: Statistics of jumping on the left leg (lower extremities marker set): Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.77	7.2	10.5	-3.3	37.4	1.5
	abduction/adduction	entire part has to be cut off					
	rotation	-0.12	7.1	25.3	-18.2	14.7	5.8
knee right	flexion/extension	0.97	11.4	14.7	-3.3	-0.4	1.2
ankle right	plantar/dorsal flexion	entire part has to be cut off					
	eversion/inversion	entire part has to be cut off					
	abduction/adduction	entire part has to be cut off					
hip left	flexion/extension	0.93	14.9	27.0	-12.1	32.2	3.5
	abduction/adduction	0.84	9.3	18.7	-9.5	-9.0	2.8
	rotation	0.19	6.3	64.3	-58.0	-12.9	17.8
knee left	flexion/extension	0.99	36.6	47.7	-11.0	5.0	3.1

ankle left	plantar/dorsal flexion	0.95	51.5	46.8	4.7	-6.3	4.3
	eversion/inversion	-0.20	12.8	24.5	-11.7	-30.4	7.4
	abduction/adduction	0.30	13.6	32.9	-19.3	-1.7	8.0

Table 53: Statistics of jumping on the right leg (lower extremities marker set): Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.71	27.1	15.1	12.0	34.8	3.3
	abduction/adduction	0.96	8.2	17.1	-8.9	2.3	2.6
	rotation	0.43	19.4	30.6	-11.1	-4.5	8.3
knee right	flexion/extension	0.99	35.2	38.9	-3.7	-1.3	1.9
ankle right	plantar/dorsal flexion	0.96	47.5	48.9	-1.4	1.3	3.5
	eversion/inversion	0.67	24.4	14.3	10.1	-1.2	5.3
	abduction/adduction	0.57	11.1	15.2	-4.1	4.2	3.5
hip left	flexion/extension	entire part has to be cut off					
	abduction/adduction	entire part has to be cut off					
	rotation	0.33	9.5	21.1	-11.6	-12.9	4.2
knee left	flexion/extension	0.94	8.6	8.2	0.3	5.6	1.2
ankle left	plantar/dorsal flexion	0.87	5.2	37.9	-32.7	-11.7	12.4
	eversion/inversion	entire part has to be cut off					
	abduction/adduction	entire part has to be cut off					

Table 54: Statistics of jumping on alternating legs (lower extremities marker set): Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.83	12.8	24.5	-11.6	35.0	3.7
	abduction/adduction	0.52	5.7	9.3	-3.7	-3.0	2.4
	rotation	0.78	15.8	39.7	-23.9	14.5	7.3
knee right	flexion/extension	1.00	81.4	87.5	-6.0	1.0	1.8
ankle right	plantar/dorsal flexion	0.92	37.9	43.3	-5.5	1.2	4.0
	eversion/inversion	0.86	23.1	12.4	10.8	-0.6	3.8
	abduction/adduction	0.44	9.2	18.2	-9.0	-0.6	5.7

hip left	flexion/extension	0.97	20.7	36.4	-15.7	27.9	4.8
	abduction/adduction	0.49	12.4	19.4	-7.1	-3.3	5.4
	rotation	0.87	20.8	61.8	-41.0	-11.2	9.0
knee left	flexion/extension	0.99	83.7	92.7	-9.1	7.6	3.6
ankle left	plantar/dorsal flexion	0.97	57.2	51.4	5.8	-1.7	3.3
	eversion/inversion	0.55	18.7	29.4	-10.7	-18.0	9.3
	abduction/adduction	-0.37	20.7	50.7	-30.0	-15.3	13.7

Table 55: Statistics of jumping jack movements (lower extremities marker set): Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.31	27.6	43.6	-16.0	-24.6	10.4
	abduction/adduction	0.92	31.3	33.3	-2.0	-6.7	3.7
	rotation	0.33	24.6	40.8	-16.2	-0.9	10.3
knee right	flexion/extension	0.98	39.3	40.5	-1.2	7.5	2.0
ankle right	plantar/dorsal flexion	0.96	40.4	60.2	-19.8	-9.0	7.3
	eversion/inversion	0.29	38.4	14.9	23.4	-13.6	7.6
	abduction/adduction	0.40	14.0	34.6	-20.5	-2.5	6.4
hip left	flexion/extension	0.41	30.8	52.9	-22.1	-17.5	11.5
	abduction/adduction	0.91	26.2	39.0	-12.8	-1.9	4.1
	rotation	0.26	23.1	30.1	-6.9	23.5	7.6
knee left	flexion/extension	0.95	46.8	46.7	0.1	1.5	4.3
ankle left	plantar/dorsal flexion	0.94	47.6	60.8	-13.2	-6.7	6.1
	eversion/inversion	0.78	21.1	16.2	4.9	11.7	3.3
	abduction/adduction	0.14	8.8	45.4	-36.6	-11.8	10.0

Table 56: Statistics of jumping on both legs (full body marker set): Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.99	98.8	113.8	-15.0	3.0	5.3
	abduction/adduction	-0.09	10.6	9.1	1.4	-3.0	4.9
	rotation	0.65	21.1	34.7	-13.6	18.0	6.2
knee right	flexion/extension	0.98	86.5	79.0	7.5	-2.1	3.1

ankle right	plantar/dorsal flexion	0.97	58.6	69.8	-11.2	4.1	4.5
	eversion/inversion	entire part has to be cut off					
	abduction/adduction	0.74	8.4	38.3	-29.8	-0.9	6.6
hip left	flexion/extension	0.99	94.8	123.8	-29.0	-0.6	7.7
	abduction/adduction	-0.21	14.7	13.2	1.5	-10.2	5.4
	rotation	0.85	25.5	45.5	-20.1	-0.8	8.3
knee left	flexion/extension	1.00	79.2	86.7	-7.4	4.3	2.4
ankle left	plantar/dorsal flexion	0.99	61.8	72.7	-10.9	5.4	4.1
	eversion/inversion	-0.01	6.5	15.8	-9.3	-4.7	3.2
	abduction/adduction	0.74	14.5	18.1	-3.6	-0.4	2.9
shoulder right	flexion/extension	0.97	90.1	103.4	-13.3	-4.0	4.1
	abduction/adduction	0.97	19.4	16.8	2.6	0.0	1.4
	rotation	0.89	58.5	87.8	-29.4	-13.9	12.6
elbow right	flexion/extension	0.91	66.7	70.1	-3.4	5.7	2.8
shoulder left	flexion/extension	0.97	82.6	104.0	-21.4	-3.8	5.6
	abduction/adduction	0.95	24.1	26.6	-2.5	1.1	2.6
	rotation	0.86	46.3	71.8	-25.5	17.2	11.7
elbow left	flexion/extension	0.85	87.8	99.5	-11.7	0.9	7.9

Table 57: Statistics of jumping on the left leg (full body marker set): Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.93	48.1	43.3	4.8	-6.7	6.4
	abduction/adduction	0.25	10.1	12.0	-1.9	-8.2	3.4
	rotation	0.38	15.0	17.9	-2.9	14.4	5.2
knee right	flexion/extension	0.96	21.0	17.5	3.5	1.9	1.9
ankle right	plantar/dorsal flexion	0.75	20.9	15.5	5.4	-1.3	3.1
	eversion/inversion	-0.07	6.9	9.5	-2.6	24.4	3.3
	abduction/adduction	0.57	6.2	8.9	-2.7	16.3	1.7
hip left	flexion/extension	0.94	74.3	72.7	1.6	-2.9	7.1
	abduction/adduction	0.03	16.8	10.1	6.7	-17.5	5.0
	rotation	0.38	17.8	45.7	-27.9	-7.2	9.2
knee left	flexion/extension	0.92	67.9	73.5	-5.6	6.2	4.3

ankle left	plantar/dorsal flexion	0.92	59.4	68.2	-8.8	2.4	4.8
	eversion/inversion	0.11	10.9	11.9	-0.9	-5.2	3.6
	abduction/adduction	0.42	12.5	29.5	-17.0	0.4	8.2
shoulder right	flexion/extension	0.97	74.3	99.8	-25.5	-14.9	6.9
	abduction/adduction	0.98	47.6	45.8	1.8	4.8	2.5
	rotation	-0.52	64.2	368.1	-303.8	57.3	140.6
elbow right	flexion/extension	-0.97	56.6	63.9	-7.3	110.1	32.6
shoulder left	flexion/extension	0.96	102.0	144.5	-42.6	-6.3	10.0
	abduction/adduction	0.97	50.4	55.2	-4.8	0.8	3.0
	rotation	0.91	94.7	138.5	-43.9	31.1	13.1
elbow left	flexion/extension	0.97	73.7	79.9	-6.2	1.7	6.0

Table 58: Statistics of jumping on the right leg (full body marker set): Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.96	63.6	75.3	-11.7	0.4	6.3
	abduction/adduction	0.74	13.4	19.5	-6.2	10.6	3.4
	rotation	0.54	23.9	30.1	-6.1	19.6	6.1
knee right	flexion/extension	0.99	70.7	73.2	-2.5	3.7	2.6
ankle right	plantar/dorsal flexion	0.90	52.9	69.0	-16.1	2.1	5.1
	eversion/inversion	-0.94	6.6	13.9	-7.3	12.9	8.0
	abduction/adduction	0.86	7.9	35.3	-27.4	1.0	6.4
hip left	flexion/extension	0.94	63.3	79.5	-16.2	-1.8	8.6
	abduction/adduction	-0.69	5.9	11.8	-6.0	1.4	5.9
	rotation	0.62	31.8	32.7	-0.9	-3.2	8.0
knee left	flexion/extension	0.95	33.3	34.7	-1.4	5.3	2.6
ankle left	plantar/dorsal flexion	0.81	20.2	18.6	1.6	-1.1	3.5
	eversion/inversion	-0.20	21.4	16.1	5.3	-20.2	7.3
	abduction/adduction	-0.30	14.8	13.2	1.7	-11.3	5.3
shoulder right	flexion/extension	0.99	114.2	144.4	-30.2	-14.9	12.2
	abduction/adduction	0.93	32.7	38.1	-5.4	0.9	3.5
	rotation	-0.36	99.9	369.9	-270.0	21.8	152.0
elbow right	flexion/extension	-0.85	59.8	52.7	7.1	151.7	27.4

shoulder left	flexion/extension	0.95	53.5	72.6	-19.2	-9.8	6.8
	abduction/adduction	0.96	51.4	49.9	1.6	0.3	3.0
	rotation	0.91	54.0	54.5	-0.6	16.4	4.9
elbow left	flexion/extension	0.90	72.4	88.3	-15.9	2.3	6.5

Table 59: Statistics of kicks and box punches: Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.85	105.7	148.8	-43.1	5.9	11.8
	abduction/adduction	0.56	54.1	76.7	-22.6	6.9	6.7
	rotation	0.26	36.3	92.3	-56.0	32.4	17.1
knee right	flexion/extension	0.92	133.3	124.7	8.6	-1.1	5.3
ankle right	plantar/dorsal flexion	0.76	30.4	60.7	-30.2	-4.0	14.1
	eversion/inversion	0.51	99.4	0.0	99.4	0.0	0.0
	abduction/adduction	0.24	43.8	0.0	43.8	0.0	0.0
hip left	flexion/extension	0.85	69.5	80.1	-10.7	2.8	11.8
	abduction/adduction	0.81	49.7	78.6	-28.9	-0.6	7.8
	rotation	0.66	56.6	107.3	-50.7	-13.3	14.6
knee left	flexion/extension	0.93	90.3	94.5	-4.3	1.5	4.8
ankle left	plantar/dorsal flexion	0.69	46.1	86.3	-40.2	4.3	8.9
	eversion/inversion	0.27	31.0	35.4	-4.4	-2.7	8.2
	abduction/adduction	0.14	22.6	78.4	-55.8	11.0	16.7
shoulder right	flexion/extension	0.94	152.4	179.1	-26.8	0.7	13.9
	abduction/adduction	0.85	85.4	83.2	2.2	-0.3	5.7
	rotation	0.43	144.8	373.9	-229.0	13.1	79.9
elbow right	flexion/extension	0.43	113.8	269.7	-155.9	42.2	85.9
shoulder left	flexion/extension	0.93	109.2	148.8	-39.6	-3.1	12.2
	abduction/adduction	0.97	101.2	90.6	10.6	-1.2	3.8
	rotation	0.80	113.3	308.8	-195.5	26.1	28.2
elbow left	flexion/extension	0.51	115.7	362.8	-247.1	23.1	80.6

Table 60: Statistics of running with big steps: Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.94	42.3	51.1	-8.8	3.8	6.6
	abduction/adduction	0.68	10.8	21.4	-10.6	2.9	4.1
	rotation	0.43	11.9	34.7	-22.7	17.9	8.4
knee right	flexion/extension	1.00	83.3	85.8	-2.5	-4.4	1.9
ankle right	plantar/dorsal flexion	0.94	46.3	47.6	-1.3	3.5	4.0
	eversion/inversion	0.43	14.0	18.9	-4.9	10.6	3.6
	abduction/adduction	0.43	13.7	36.2	-22.4	-2.4	10.2
hip left	flexion/extension	0.88	42.4	48.1	-5.7	1.2	6.3
	abduction/adduction	0.81	12.8	27.6	-14.8	-2.4	4.9
	rotation	0.78	16.3	36.2	-19.9	-8.2	6.1
knee left	flexion/extension	1.00	79.6	82.9	-3.3	-0.6	2.0
ankle left	plantar/dorsal flexion	0.96	54.8	57.4	-2.7	-2.6	3.8
	eversion/inversion	0.31	10.8	29.0	-18.3	-11.5	7.1
	abduction/adduction	-0.03	15.2	40.9	-25.6	4.3	10.9
shoulder right	flexion/extension	0.98	37.8	45.1	-7.3	8.6	3.1
	abduction/adduction	0.98	26.0	30.5	-4.5	0.0	2.3
	rotation	0.91	27.1	34.7	-7.6	-21.6	4.1
elbow right	flexion/extension	0.94	31.5	33.2	-1.7	-13.2	2.4
shoulder left	flexion/extension	0.97	39.6	53.6	-14.0	11.5	3.5
	abduction/adduction	0.38	10.8	9.5	1.3	0.6	2.6
	rotation	0.47	20.2	27.9	-7.7	36.5	7.2
elbow left	flexion/extension	0.70	17.7	24.7	-6.9	-5.6	4.2

Table 61: Statistics of running with small steps: Markerless data compared to marker-based data excluding parts with small ranges of motion.

Joint	Movement	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
hip right	flexion/extension	0.86	36.1	50.5	-14.4	-5.3	7.5
	abduction/adduction	0.43	7.1	17.0	-9.9	3.4	4.0
	rotation	-0.51	5.1	27.6	-22.5	19.2	9.4
knee right	flexion/extension	1.00	58.4	64.2	-5.8	-4.1	2.1

ankle right	plantar/dorsal flexion	0.87	20.7	25.3	-4.6	4.4	4.0
	eversion/inversion	0.43	10.4	11.3	-0.9	9.0	3.2
	abduction/adduction	0.58	6.3	31.8	-25.5	-4.7	9.0
hip left	flexion/extension	0.80	35.0	44.4	-9.3	-9.3	7.8
	abduction/adduction	0.71	7.8	18.3	-10.5	-3.2	3.8
	rotation	0.54	7.9	23.1	-15.2	-2.3	5.5
knee left	flexion/extension	1.00	59.6	65.3	-5.7	1.4	1.8
ankle left	plantar/dorsal flexion	0.98	19.6	26.2	-6.6	-2.4	2.3
	eversion/inversion	0.28	8.1	23.9	-15.9	-11.1	6.4
	abduction/adduction	0.09	5.6	26.7	-21.1	-3.0	8.3
shoulder right	flexion/extension	0.92	28.4	22.4	6.0	15.0	3.6
	abduction/adduction	0.94	14.9	16.5	-1.6	-1.5	1.2
	rotation	0.64	15.6	13.4	2.1	-18.7	3.9
elbow right	flexion/extension	0.95	33.8	32.7	1.2	-16.6	2.5
shoulder left	flexion/extension	-0.34	13.2	94.6	-81.4	346.4	23.8
	abduction/adduction	entire part has to be cut off					
	rotation	0.69	5.2	67.0	-61.8	16.4	19.7
elbow left	flexion/extension	0.94	38.8	45.7	-6.9	10.2	3.6

C.5 Statistics of hybrid vs. marker-based data of specific joint movements

Table 62: Statistics of specific joint movements with big amplitudes: Marker-based data compared to hybrid data of hip joint angles. The first row of each movement and marker combination presents values of the right body side, the second row values of the left body side.

Movement	Markers	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
flexion/ extension	3 pelvis	1.00	86.3	81.5	4.8	-0.1	2.0
		0.99	93.3	88.3	5.0	0.8	3.2
abduction/ adduction	3 pelvis	0.99	54.1	54.2	-0.2	-7.8	1.9
		0.99	54.2	54.6	-0.5	-8.3	2.0
rotation	3 pelvis, lat. knee	0.96	49.4	56.2	-6.9	0.6	2.6
		0.97	58.3	65.4	-7.1	-15.5	4.0
	3 pelvis, lat. and med. knee	0.99	49.4	51.0	-1.6	-1.4	1.3
		0.98	58.3	60.7	-2.4	-15.4	3.3

Table 63: Statistics of specific joint movements with big amplitudes: Marker-based data compared to hybrid data of ankle joint angles. The first row of each movement and marker combination presents values of the right body side, the second row values of the left body side.

Movement	Markers	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
plantar/ dorsal flexion	forefoot	0.98	65.9	58.5	7.4	-1.9	3.7
		0.98	65.6	57.0	8.5	1.9	3.8
	forefoot, heel	0.99	65.9	59.7	6.2	-0.8	2.6
		0.99	65.6	58.1	7.5	2.1	3.3
eversion/ inversion	lat. ankle	0.94	18.7	15.6	3.1	3.7	2.1
		0.91	16.1	6.3	9.8	-5.5	3.7
	lat. and med. ankle	0.92	18.7	9.5	9.3	8.1	3.7
		0.97	16.1	10.9	5.2	-9.6	2.0
abduction adduction	lat. and med. knee, forefoot, heel	0.99	18.3	34.7	-16.5	-1.9	6.1
		0.94	28.0	34.0	-6.0	13.5	5.3
	lat. and med. knee	0.92	18.3	33.3	-15.0	1.5	5.0
		0.96	28.0	33.7	-5.7	12.1	3.1
	lat. knee	0.89	18.3	27.7	-9.4	4.5	3.2
		0.93	28.0	36.2	-8.1	7.2	3.8
	lat. and med. knee, forefoot	0.96	18.3	34.3	-16.0	-1.1	5.8
		0.94	28.0	40.3	-12.2	13.1	5.5

Table 64: Statistics of specific joint movements with big amplitudes: Marker-based data compared to hybrid data of shoulder joint angles. The first row of each movement and marker combination presents values of the right body side, the second row values of the left body side.

Movement	Markers	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
abduction/ adduction	triceps	0.82	84.6	66.2	18.4	-10.5	12.6
		0.90	80.2	65.7	14.5	3.5	8.2
	lat. elbow, triceps	0.93	84.6	67.1	17.4	-5.3	7.5
		0.95	80.2	72.2	8.0	-0.2	5.5
rotation	triceps	0.99	52.5	60.2	-7.7	42.9	1.6
		1.00	73.8	78.5	-4.7	-45.2	3.1
	lat. elbow, triceps	0.99	52.5	59.3	-6.8	43.9	2.4
		0.99	73.8	73.5	0.3	-48.2	2.4

Table 65: Statistics of specific joint movements with big amplitudes: Marker-based data compared to hybrid data of elbow joint angles. The first row of each movement and marker combination presents values of the right body side, the second row values of the left body side.

Movement	Markers	Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
flexion/ extension	triceps	0.99	134.1	142.0	-7.8	1.0	4.4
		0.99	151.7	151.2	0.5	14.0	7.1
	lat. elbow, triceps	0.99	134.1	143.3	-9.2	-4.5	4.0
		0.99	151.7	151.1	0.6	5.2	7.1
	lat. elbow, trizeps, lat. and med. wrist	1.00	134.1	138.7	-4.6	-3.0	3.6
		0.99	156.4	152.5	4.0	4.7	7.1

C.6 Statistics of hybrid vs. marker-based data of complex movements

Table 66: Statistics of complex movements: Marker-based data compared to hybrid data of hip flexion/extension angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
3 pelvis	biking		0.99	38.6	31.3	7.3	1.7	3.1
			1.00	38.0	38.6	-0.6	2.5	0.9
	jumping (lower extremities)	jumps on both legs	0.99	20.8	26.4	-5.6	27.4	1.3
			1.00	23.5	26.4	-2.9	20.7	1.4
		jumps on left leg	0.95	7.2	6.0	1.3	43.6	0.7
			0.96	15.1	15.0	0.1	24.4	1.1
		jumps on right leg	0.96	14.4	11.4	3.0	34.2	1.2
			0.60	4.5	6.4	-2.0	30.9	1.2
		jumps on alternating legs	0.95	13.2	16.3	-3.1	36.3	1.5
			0.97	20.7	28.3	-7.6	25.6	3.1
	jumping jack		0.98	27.6	28.7	-1.1	-4.9	1.4
			0.98	30.8	23.1	7.7	-1.3	1.5
	jumping (full body)	jumps on both legs	1.00	99.7	112.2	-12.5	13.5	3.5
			1.00	94.4	97.4	-3.0	13.6	2.0
		jumps on left leg	0.96	48.1	45.4	2.7	12.6	3.2
			1.00	74.3	73.0	1.3	14.5	1.4
		jumps on right leg	1.00	63.6	68.6	-5.0	12.7	1.8
			1.00	63.3	63.3	0.0	11.0	1.4

3 pelvis	kicks and punches		1.00	105.7	112.0	-6.3	-14.7	2.2
			0.99	69.5	78.0	-8.5	-10.1	2.6
	running	big steps	1.00	42.3	44.1	-1.9	-0.6	0.8
			0.99	42.4	44.2	-1.9	-4.2	1.2
		small steps	1.00	36.1	37.9	-1.8	-1.3	0.8
			1.00	35.0	34.8	0.3	-4.3	1.2

Table 67: Statistics of complex movements: Marker-based data compared to hybrid data of hip abduction/adduction angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
3 pelvis	biking		0.99	7.3	6.8	0.4	-7.0	0.4
			0.97	5.5	3.8	1.7	-11.0	0.8
	jumping (lower extremi-ties)	jumps on both legs	-0.08	3.9	4.5	-0.6	2.4	1.4
			0.93	4.1	4.7	-0.6	3.1	0.4
		jumps on left leg	0.89	5.6	8.4	-2.8	-3.8	1.1
			0.91	9.3	16.7	-7.5	-9.1	3.0
		jumps on right leg	0.94	8.2	4.7	3.5	-7.9	1.3
			0.76	2.8	2.7	0.1	-7.3	0.6
		jumps on alternating legs	0.70	9.0	10.4	-1.4	-6.8	1.6
			0.96	13.6	12.1	1.4	-7.5	1.4
	jumping jack		1.00	31.3	37.4	-6.1	1.2	1.1
			0.99	26.2	26.6	-0.4	3.6	1.1
	jumping (full body)	jumps on both legs	0.96	13.3	12.4	0.9	2.4	1.0
			0.96	15.8	14.7	1.1	-4.7	1.5
		jumps on left leg	0.95	11.4	9.4	1.9	3.5	1.2
			0.84	16.8	17.8	-1.0	-3.9	2.0
		jumps on right leg	0.97	18.7	16.9	1.9	3.7	1.0
			0.91	9.0	8.2	0.8	-3.2	0.8
	kicks and punches		0.98	54.1	55.3	-1.2	3.9	1.5
			0.97	49.7	48.9	0.8	-5.1	1.8
	running	big steps	0.89	10.8	9.6	1.2	3.0	0.8
			0.96	12.8	14.6	-1.8	-3.3	1.1
		small steps	0.99	7.8	8.7	-1.0	7.3	0.5
			0.98	7.8	7.9	0.0	0.8	0.3

Table 68: Statistics of complex movements: Marker-based data compared to hybrid data of hip rotation angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
3 pelvis, lat. knee	biking		0.60	7.7	2.8	4.9	12.2	1.6
			0.69	6.3	16.6	-10.3	0.0	4.8
	jumping (lower extremi-ties)	jumps on both legs	0.52	7.7	34.8	-27.1	35.5	8.0
			0.72	8.2	14.9	-6.6	-14.1	2.2
		jumps on left leg	0.47	8.3	3.6	4.7	14.3	2.1
			0.57	8.1	17.1	-9.0	-4.7	3.2
		jumps on right leg	0.32	19.4	12.1	7.3	-8.1	5.3
			0.72	10.1	16.0	-6.0	-10.3	2.4
		jumps on alternating legs	0.61	16.1	16.4	-0.3	8.3	3.7
			0.44	20.8	22.6	-1.8	-14.4	4.8
	jumping jack		0.78	24.6	28.5	-3.9	7.9	5.1
			0.41	23.1	43.1	-19.9	24.8	7.1
	jumping (full body)	jumps on both legs	0.91	21.1	35.0	-13.9	15.2	3.9
			0.83	28.8	25.5	3.3	0.5	4.0
		jumps on left leg	0.86	16.3	18.5	-2.2	16.2	2.7
			0.85	25.4	17.8	7.6	1.1	3.8
		jumps on right leg	0.92	23.9	34.8	-10.8	18.1	4.4
			0.96	39.8	36.3	3.6	6.2	3.2
	kicks and punches		0.84	36.3	66.5	-30.2	22.5	6.3
			0.90	56.6	85.8	-29.3	-25.9	7.3
	running	big steps	0.48	11.9	34.1	-22.2	33.7	8.1
			0.63	16.3	32.3	-16.0	1.9	7.6
		small steps	-0.38	6.2	17.4	-11.2	12.1	6.2
			0.48	7.9	18.6	-10.7	-8.1	5.2
3 pelvis, lat. and med. knee	biking		0.81	7.7	5.3	2.4	11.8	1.0
			0.81	6.3	10.1	-3.7	-2.3	2.3
	jumping (lower extremi-ties)	jumps on both legs	0.62	7.7	23.1	-15.4	42.1	3.8
			0.90	8.2	14.6	-6.4	-19.3	1.6
		jumps on left leg	0.97	8.3	6.3	2.0	15.9	0.8
			0.85	8.1	11.2	-3.1	-1.5	1.4
		jumps on right leg	0.97	19.4	16.6	2.8	-1.1	1.7
			0.98	10.1	14.9	-4.8	-8.6	1.1
		jumps on alternating legs	0.96	16.1	16.0	0.2	8.1	1.1
			0.92	20.8	18.6	2.3	-9.5	1.9
	jumping jack		0.90	24.6	19.9	4.6	6.3	2.4
			0.83	23.1	41.7	-18.5	22.9	3.7

3 pelvis, lat. and med. knee	jumping (full body)	jumps on both legs	0.93	21.1	24.6	-3.5	18.0	2.0
			0.91	22.5	28.8	-6.2	-5.2	3.8
		jumps on left leg	0.96	16.4	13.1	3.3	14.0	1.8
			0.90	17.8	24.5	-6.7	-1.3	3.5
		jumps on right leg	0.90	23.9	15.2	8.7	19.5	2.5
			0.98	36.3	30.0	6.2	7.6	2.7
	kicks and punches		0.98	36.3	52.0	-15.7	24.3	2.6
			0.99	56.6	61.9	-5.4	-10.6	1.5
	running	big steps	0.81	11.9	16.1	-4.2	34.6	2.4
			0.82	16.3	18.2	-1.9	-3.6	2.7
		small steps	0.47	6.2	6.9	-0.6	14.9	1.5
			0.75	7.9	15.4	-7.5	-4.7	3.3

Table 69: Statistics of complex movements: Marker-based data compared to hybrid data of hip flexion/extension angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	**Recording**		**Corre-lation**	**Angle range Motion [°]**	**Angle range Shape [°]**	**Angle range difference [°]**	**MV angle difference [°]**	**SD angle difference [°]**
3 pelvis	biking		0.99	38.6	31.3	7.3	1.7	3.1
			1.00	38.0	38.6	-0.6	2.5	0.9
	jumping (lower extremi-ties)	jumps on both legs	0.99	20.8	26.4	-5.6	27.4	1.3
			1.00	23.5	26.4	-2.9	20.7	1.4
		jumps on left leg	0.95	7.2	6.0	1.3	43.6	0.7
			0.96	15.1	15.0	0.1	24.4	1.1
		jumps on right leg	0.96	14.4	11.4	3.0	34.2	1.2
			entire part has to be cut off					
		jumps on alternating legs	0.95	13.2	16.3	-3.1	36.3	1.5
			0.97	20.7	28.3	-7.6	25.6	3.1
	jumping jack		0.98	27.6	28.7	-1.1	-4.9	1.4
			0.98	30.8	23.1	7.7	-1.3	1.5
	jumping (full body)	jumps on both legs	1.00	99.7	112.2	-12.5	13.5	3.5
			1.00	94.4	97.4	-3.0	13.6	2.0
		jumps on left leg	0.96	48.1	45.4	2.7	12.6	3.2
			1.00	74.3	73.0	1.3	14.5	1.4
		jumps on right leg	1.00	63.6	68.6	-5.0	12.7	1.8
			1.00	63.3	63.3	0.0	11.0	1.4
	kicks and punches		1.00	105.7	112.0	-6.3	-14.7	2.2
			0.99	69.5	78.0	-8.5	-10.1	2.6
	running	big steps	1.00	42.3	44.1	-1.9	-0.6	0.8
			0.99	42.4	44.2	-1.9	-4.2	1.2
		small steps	1.00	36.1	37.9	-1.8	-1.3	0.8
			1.00	35.0	34.8	0.3	-4.3	1.2

Table 70: Statistics of complex movements: Marker-based data compared to hybrid data of hip abduction/adduction angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
3 pelvis	biking		0.99	7.3	6.8	0.4	-7.0	0.4
			0.97	5.5	3.8	1.7	-11.0	0.8
	jumping (lower extremi-ties)	jumps on both legs	entire part has to be cut off					
			0.93	4.1	4.7	-0.6	3.1	0.4
		jumps on left leg	entire part has to be cut off					
			0.91	9.3	16.7	-7.5	-9.1	3.0
		jumps on right leg	0.94	8.2	4.7	3.5	-7.9	1.3
			entire part has to be cut off					
		jumps on alternating legs	0.55	5.8	6.5	-0.7	-1.5	2.9
			0.96	13.6	12.1	1.4	-7.5	1.4
	jumping jack		1.00	31.3	37.4	-6.1	1.2	1.1
			0.99	26.2	26.6	-0.4	3.6	1.1
	jumping (full body)	jumps on both legs	0.96	13.3	12.4	0.9	2.4	1.0
			0.96	15.8	14.7	1.1	-4.7	1.5
		jumps on left leg	0.95	11.4	9.4	1.9	3.5	1.2
			0.93	16.8	17.8	-1.0	-3.0	1.8
		jumps on right leg	0.97	18.7	16.9	1.9	3.7	1.0
			0.91	9.0	8.2	0.8	-3.2	0.8
	kicks and punches		0.98	54.1	55.3	-1.2	3.9	1.5
			0.97	49.7	48.9	0.8	-5.1	1.8
	running	big steps	0.93	10.8	9.6	1.2	1.9	1.6
			0.96	12.8	14.6	-1.8	-3.3	1.1
		small steps	0.99	7.8	8.7	-1.0	7.3	0.5
			0.98	7.8	7.9	0.0	0.8	0.3

Table 71: Statistics of complex movements: Marker-based data compared to hybrid data of hip rotation angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
3 pelvis, lat. knee	biking		entire part has to be cut off					
			entire part has to be cut off					
	jumping (lower extremi-ties)	jumps on both legs	0.66	7.7	33.7	-26.0	34.5	8.5
			0.72	8.2	14.9	-6.6	-14.1	2.2
		jumps on left leg	0.52	7.1	3.6	3.5	14.0	2.0
			0.50	6.3	17.1	-10.8	-4.7	3.3

3 pelvis, lat. knee	jumping (lower extremities)	jumps on right leg	0.32	19.4	12.1	7.3	-8.1	5.3
			0.65	9.5	16.0	-6.6	-10.0	2.4
		jumps on alternating legs	0.60	16.1	16.4	-0.3	7.9	4.1
			0.59	20.8	22.6	-1.8	-14.5	5.1
	jumping jack		0.78	24.6	28.5	-3.9	7.9	5.1
			0.41	23.1	43.1	-19.9	24.8	7.1
	jumping (full body)	jumps on both legs	0.91	21.1	35.0	-13.9	15.2	3.9
			0.83	28.8	25.5	3.3	0.5	4.0
		jumps on left leg	0.69	15.1	17.7	-2.6	17.7	2.7
			0.85	25.4	17.8	7.6	1.1	3.8
		jumps on right leg	0.92	23.9	34.8	-10.8	18.1	4.4
			0.96	39.8	36.3	3.6	6.2	3.2
	kicks and punches		0.84	36.3	66.5	-30.2	22.5	6.3
			0.90	56.6	85.8	-29.3	-25.9	7.3
	running	big steps	-0.38	6.2	17.4	-11.2	12.1	6.2
			0.62	16.3	29.1	-12.8	-5.4	6.8
		small steps	entire part has to be cut off					
			0.55	7.9	18.3	-10.4	-7.0	4.8
3 pelvis, lat. and med. knee	biking		entire part has to be cut off					
			entire part has to be cut off					
	jumping (lower extremities)	jumps on both legs	0.90	7.7	16.7	-9.1	42.0	2.8
			0.90	8.2	14.6	-6.4	-19.3	1.6
		jumps on left leg	0.97	8.3	6.3	2.0	15.9	0.8
			0.87	6.3	11.2	-4.9	-1.1	1.1
		jumps on right leg	0.97	19.4	16.6	2.8	-1.1	1.7
			0.98	10.1	14.9	-4.8	-8.6	1.1
		jumps on alternating legs	0.96	16.1	16.0	0.2	8.1	1.1
			0.92	20.8	18.6	2.3	-9.5	1.9
	jumping jack		0.90	24.6	19.9	4.6	6.3	2.4
			0.83	23.1	41.7	-18.5	22.9	3.7
	jumping (full body)	jumps on both legs	0.93	21.1	24.6	-3.5	18.0	2.0
			0.91	22.5	28.8	-6.2	-5.2	3.8
		jumps on left leg	0.96	16.4	13.1	3.3	14.0	1.8
			0.90	17.8	24.5	-6.7	-1.3	3.5
		jumps on right leg	0.90	23.9	15.2	8.7	19.5	2.5
			0.98	36.3	30.0	6.2	7.6	2.7
	kicks and punches		0.98	36.3	52.0	-15.7	24.3	2.6
			0.99	56.6	61.9	-5.4	-10.6	1.5
	running	big steps	0.82	11.9	14.6	-2.6	34.1	2.2
			0.82	16.3	18.2	-1.9	-3.6	2.7
		small steps	entire part has to be cut off					
			0.75	7.9	15.4	-7.5	-4.7	3.3

Table 72: Statistics of complex movements: Marker-based data compared to hybrid data (equally weighted silhouette- and marker-correspondences) of hip rotation angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
3 pelvis, lat. and med. knee	biking		0.86	7.7	17.9	-10.2	48.5	1.3
			0.92	6.3	7.1	-0.8	-3.6	1.0
	jumping (lower extremities)	jumps on both legs	0.80	7.7	15.2	-7.5	48.6	1.7
			0.81	8.2	6.9	1.3	-22.6	1.3
		jumps on left leg	0.99	8.3	9.1	-0.8	16.7	0.4
			0.75	8.1	9.2	-1.1	0.0	1.6
		jumps on right leg	0.99	19.4	20.1	-0.7	2.1	1.0
			1.00	10.1	14.1	-4.1	-6.6	0.6
		jumps on alternating legs	0.96	16.1	16.0	0.2	8.1	1.1
			0.92	20.8	18.6	2.3	-9.5	1.9
	jumping jack		0.89	24.6	18.4	6.2	5.7	2.4
			0.90	23.1	41.5	-18.4	23.3	3.0
	jumping (full body)	jumps on both legs	0.84	21.1	18.0	3.1	23.1	2.8
			0.94	25.5	25.6	-0.2	-4.4	2.1
		jumps on left leg	0.92	16.4	14.0	2.4	13.2	2.2
			0.92	17.8	23.2	-5.4	-0.4	2.7
		jumps on right leg	0.94	23.9	15.6	8.3	15.8	2.4
			0.98	36.3	30.9	5.4	7.7	2.7
	kicks and punches		0.98	36.3	52.0	-15.7	24.3	2.6
			0.99	56.6	61.1	-4.5	-10.6	1.3
	running	big steps	0.93	11.9	14.5	-2.6	29.5	1.0
			0.97	16.3	13.8	2.5	-14.4	0.9
		small steps	0.97	6.2	7.7	-1.4	9.2	0.5
			0.81	7.9	7.2	0.7	-9.8	1.2

Table 73: Statistics of complex movements: Marker-based data compared to hybrid data (equally weighted silhouette- and marker-correspondences) of hip rotation angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
3 pelvis, lat. and med. knee	biking		entire part has to be cut off					
			0.92	6.3	7.1	-0.8	-3.6	1.0
	jumping (lower extremities)	jumps on both legs	0.91	7.7	17.9	-10.2	48.6	1.2
			0.81	8.2	6.9	1.3	-22.6	1.3
		jumps on left leg	0.99	8.3	9.1	-0.8	16.7	0.4
			0.95	6.3	9.2	-2.9	0.4	0.6

3 pelvis, lat. and med. knee	jumping (lower extremities)	jumps on right leg	0.99	19.4	20.1	-0.7	2.1	1.0
			1.00	10.1	14.1	-4.1	-6.6	0.6
		jumps on alternating legs	0.96	16.1	16.0	0.2	8.1	1.1
			0.92	20.8	18.6	2.3	-9.5	1.9
	jumping jack		0.89	24.6	18.4	6.2	5.7	2.4
			0.90	23.1	41.5	-18.4	23.3	3.0
	jumping (full body)	jumps on both legs	0.84	21.1	18.0	3.1	23.1	2.8
			0.94	25.5	25.6	-0.2	-4.4	2.1
		jumps on left leg	0.92	16.4	14.0	2.4	13.2	2.2
			0.92	17.8	23.2	-5.4	-0.4	2.7
		jumps on right leg	0.94	23.9	15.6	8.3	15.8	2.4
			0.98	36.3	30.9	5.4	7.7	2.7
	kicks and punches		0.98	36.3	52.0	-15.7	24.3	2.6
			0.99	56.6	61.1	-4.5	-10.6	1.3
	running	big steps	0.93	11.9	14.5	-2.6	29.5	1.0
			0.97	16.3	13.8	2.5	-14.4	0.9
		small steps	0.97	6.2	7.7	-1.4	9.2	0.5
			0.81	7.9	7.2	0.7	-9.8	1.2

Table 74: Statistics of complex movements: Markerbased data compared to hybrid data of ankle plantar/dorsal flexion angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
forefoot	biking		0.98	42.7	51.6	-8.9	-5.1	3.3
			0.91	14.0	24.5	-10.5	1.7	3.5
	jumping (lower extremities)	jumps on both legs	0.91	49.1	46.0	3.1	7.3	6.3
			0.84	54.1	61.8	-7.7	6.6	10.8
		jumps on left leg	0.55	5.3	8.4	-3.1	-16.4	1.8
			0.96	51.8	55.3	-3.5	7.6	8.0
		jumps on right leg	0.91	47.5	46.3	1.2	3.3	7.6
			0.03	6.0	14.1	-8.1	-1.2	3.5
		jumps on alternating legs	0.94	38.1	38.5	-0.4	7.2	4.9
			0.97	57.2	54.2	3.0	-2.6	7.2
	jumping jack		0.95	40.4	59.1	-18.7	-7.0	7.7
			0.94	47.8	56.6	-8.8	-5.4	5.6
	jumping (full body)	jumps on both legs	0.99	58.6	70.4	-11.8	-4.4	4.7
			0.98	61.8	70.8	-9.0	-5.0	3.7
		jumps on left leg	0.88	20.9	25.0	-4.0	-4.4	2.1
			0.96	59.4	71.1	-11.7	-3.5	4.8
		jumps on right leg	0.93	52.9	68.6	-15.7	-3.1	5.3
			0.75	20.2	24.0	-3.8	-10.1	5.3

forefoot	kicks and punches		0.85	81.6	69.6	12.0	7.7	7.7
			0.83	46.1	56.3	-10.2	7.5	5.4
	running	big steps	0.94	46.3	49.0	-2.7	3.6	3.4
			0.96	54.8	58.9	-4.1	-5.6	3.6
		small steps	0.92	20.7	23.5	-2.8	-0.4	2.7
			0.94	19.6	22.4	-2.9	-6.0	2.4
forefoot, heel	biking		0.99	42.7	42.1	0.5	-7.7	1.3
			0.95	14.0	17.3	-3.3	3.5	1.2
	jumping (lower extremi-ties)	jumps on both legs	1.00	49.1	52.2	-3.1	-3.9	1.9
			0.99	54.1	54.7	-0.6	-0.4	2.5
		jumps on left leg	0.48	5.3	10.8	-5.5	-8.2	2.0
			0.98	51.8	49.4	2.4	-10.9	3.6
		jumps on right leg	0.98	47.5	43.3	4.2	-4.8	3.5
			0.66	6.0	15.6	-9.6	5.5	2.3
		jumps on alternating legs	0.95	38.1	44.2	-6.1	1.9	2.1
			0.97	57.2	53.6	3.6	2.8	4.0
	jumping jack		0.99	40.4	46.5	-6.0	-19.1	2.0
			0.98	47.8	50.0	-2.3	-7.2	3.0
	jumping (full body)	jumps on both legs	0.99	58.6	64.9	-6.3	0.5	2.6
			0.98	61.8	64.8	-3.0	-0.2	2.0
		jumps on left leg	0.95	20.9	24.6	-3.6	-7.9	1.3
			0.95	59.4	63.6	-4.2	-2.2	2.4
		jumps on right leg	0.96	52.9	63.2	-10.3	0.5	2.9
			0.88	20.2	22.8	-2.6	-10.2	3.1
	kicks and punches		0.88	81.6	63.4	18.1	-0.9	4.5
			0.91	46.1	41.7	4.5	3.7	4.0
	running	big steps	0.98	46.3	43.8	2.5	-2.2	2.2
			0.99	54.8	59.4	-4.6	1.5	1.9
		small steps	0.96	20.7	20.5	0.1	0.6	1.6
			0.94	19.6	19.9	-0.3	-3.7	1.9

Table 75: Statistics of complex movements: Marker-based data compared to hybrid data of ankle eversion/inversion angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
lat. ankle	biking		-0.49	8.9	10.7	-1.8	21.2	5.3
			0.28	4.5	12.9	-8.4	14.4	2.2
	jumping (lower extremi-ties)	jumps on both legs	0.44	21.7	6.5	15.2	-1.9	6.7
			0.03	17.1	20.2	-3.1	-15.7	6.2
		jumps on left leg	0.19	3.2	13.7	-10.5	25.8	3.5
			0.65	12.8	18.0	-5.2	-11.3	4.1

lat. ankle	jumping (lower extremi-ties)	jumps on right leg	0.78	26.1	19.1	7.0	1.2	4.0
			-0.41	3.5	22.7	-19.3	-25.3	5.8
		jumps on alternating legs	-0.26	22.7	23.1	-0.3	7.7	10.9
			0.81	18.7	22.7	-4.0	-18.4	3.4
	jumping jack		0.14	38.4	15.9	22.5	-11.7	7.9
			0.44	21.1	15.8	5.3	9.7	5.0
	jumping (full body)	jumps on both legs	0.72	6.9	10.2	-3.3	4.1	2.2
			0.13	6.5	14.2	-7.6	4.5	3.9
		jumps on left leg	0.31	7.8	16.8	-9.1	11.1	3.5
			0.45	10.9	8.8	2.2	-1.1	2.3
		jumps on right leg	-0.45	7.8	10.7	-2.8	7.4	4.6
			-0.07	21.4	11.9	9.5	-8.3	6.1
	kicks and punches		0.46	23.6	25.9	-2.3	7.4	5.3
			0.43	32.5	27.9	4.7	-0.1	5.5
	running	big steps	0.52	14.0	26.3	-12.3	13.5	4.1
			0.34	10.8	19.4	-8.6	-8.2	3.4
		small steps	0.37	10.4	21.0	-10.7	10.2	5.4
			0.35	8.1	16.2	-8.2	-9.6	3.9
lat. and med. ankle	biking		-0.01	8.9	5.7	3.2	15.1	3.1
			0.48	4.5	6.8	-2.3	9.2	1.5
	jumping (lower extremi-ties)	jumps on both legs	0.93	21.7	16.7	5.0	3.4	4.0
			0.36	17.1	10.5	6.6	-12.0	3.5
		jumps on left leg	0.57	3.2	4.0	-0.8	18.0	1.0
			0.77	12.8	18.6	-5.8	-19.5	3.5
		jumps on right leg	0.85	26.1	20.7	5.4	-3.8	4.6
			-0.07	3.5	11.2	-7.8	-10.0	4.1
		jumps on alternating legs	-0.02	22.7	8.9	13.8	16.0	5.7
			0.54	18.7	11.2	7.5	-11.8	3.6
	jumping jack		0.83	38.4	10.9	27.4	-9.0	6.9
			0.39	21.1	13.9	7.2	9.7	5.0
	jumping (full body)	jumps on both legs	0.69	6.9	9.3	-2.4	5.5	1.4
			0.40	6.5	14.1	-7.5	4.1	2.8
		jumps on left leg	0.13	7.8	11.8	-4.0	9.4	2.3
			-0.15	10.9	11.0	-0.1	1.1	3.8
		jumps on right leg	-0.07	7.8	11.0	-3.2	11.9	3.2
			0.28	21.4	4.5	16.9	0.4	4.6
	kicks and punches		0.68	23.6	28.8	-5.2	10.2	4.8
			0.38	32.5	19.5	13.0	-2.9	5.5
	running	big steps	0.57	14.0	14.0	0.0	9.8	2.7
			-0.04	10.8	14.8	-4.1	-4.4	4.5
		small steps	0.40	10.4	15.3	-5.0	8.9	3.9
			0.19	8.1	7.4	0.7	-0.3	2.5

Table 76: Statistics of complex movements: Marker-based data compared to hybrid data of ankle abduction/adduction angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
lat. and med. knee	biking		0.84	15.3	24.3	-9.0	-3.4	3.1
			0.66	16.0	14.5	1.5	-11.9	3.5
	jumping (lower extremities)	jumps on both legs	0.67	9.4	35.6	-26.3	4.9	5.2
			0.80	12.7	27.2	-14.5	-25.9	5.2
		jumps on left leg	0.83	2.2	4.1	-1.9	12.9	0.7
			0.85	13.6	17.0	-3.5	-8.5	2.2
		jumps on right leg	0.56	11.1	15.6	-4.5	-3.5	3.6
			0.30	1.4	9.5	-8.0	-27.9	2.6
		jumps on alternating legs	-0.34	10.5	32.3	-21.7	-8.2	11.2
			0.55	29.9	32.8	-2.9	-10.2	8.4
	jumping jack		0.83	14.0	47.5	-33.5	-20.8	6.6
			0.08	8.8	41.5	-32.8	-7.3	9.5
	jumping (full body)	jumps on both legs	0.83	8.6	60.2	-51.6	14.9	18.3
			0.89	14.5	12.7	1.8	1.9	3.0
		jumps on left leg	0.50	6.2	20.7	-14.5	10.1	4.3
			0.67	12.5	31.9	-19.4	3.1	7.0
		jumps on right leg	0.54	8.5	26.1	-17.6	0.5	5.1
			-0.69	14.8	33.0	-18.2	-8.7	7.3
	kicks and punches		0.23	30.4	143.1	-112.7	5.2	11.3
			0.25	23.5	81.0	-57.5	9.1	13.7
	running	big steps	0.54	13.7	77.9	-64.2	4.0	24.1
			0.02	15.2	85.7	-70.4	-9.2	28.2
		small steps	0.55	6.3	21.2	-14.9	4.2	4.7
			0.16	5.6	54.2	-48.6	-6.6	17.4
lat. and med. knee, forefoot	biking		0.84	15.3	21.9	-6.6	-3.4	2.3
			0.83	16.0	11.8	4.1	-13.9	2.2
	jumping (lower extremities)	jumps on both legs	0.85	22.8	35.6	-12.9	1.9	4.5
			0.94	12.7	22.8	-10.1	-15.4	3.4
		jumps on left leg	0.85	2.2	13.9	-11.7	30.7	2.1
			0.94	13.6	16.1	-2.5	-9.4	1.3
		jumps on right leg	0.79	11.1	16.5	-5.4	2.7	2.6
			0.81	1.4	3.7	-2.3	-23.1	0.7
		jumps on alternating legs	-0.23	10.5	24.3	-13.7	-5.7	7.0
			0.68	20.7	29.0	-8.2	-12.1	6.3
	jumping jack		0.73	14.0	37.1	-23.1	-13.9	5.3
			0.09	8.8	38.3	-29.5	-14.9	10.5

	jumping (full body)	jumps on both legs	0.87	8.6	47.2	-38.6	10.8	11.8
			0.97	14.5	17.3	-2.8	0.9	1.9
		jumps on left leg	0.56	6.2	14.7	-8.4	8.2	3.2
			0.66	12.5	30.6	-18.1	2.6	7.3
		jumps on right leg	0.29	8.5	22.7	-14.2	2.6	4.4
			-0.22	14.8	26.9	-12.1	-3.9	5.8
	kicks and punches		0.19	30.4	53.7	-23.3	5.2	9.9
			0.36	23.5	59.6	-36.1	7.2	9.1
	running	big steps	0.55	13.7	79.5	-65.8	6.4	22.8
			0.10	15.2	81.5	-66.3	-7.1	24.6
		small steps	0.55	6.3	19.1	-12.8	2.6	4.4
			0.10	5.6	37.9	-32.3	-5.2	11.6
lat. and med. knee, forefoot, heel	biking		0.79	15.3	12.5	2.8	2.6	3.0
			0.86	16.0	7.7	8.3	-9.1	4.7
	jumping (lower extremi-ties)	jumps on both legs	0.75	9.4	21.3	-11.9	0.4	2.7
			0.89	12.7	10.7	2.1	-14.6	1.8
		jumps on left leg	0.74	2.2	10.1	-7.9	28.3	1.5
			0.49	13.6	9.4	4.1	-11.4	3.9
		jumps on right leg	0.78	11.1	14.4	-3.4	4.0	2.5
			0.77	1.4	3.0	-1.6	-27.2	0.5
		jumps on alternating legs	-0.37	10.5	20.8	-10.3	-3.8	7.2
			0.81	20.7	11.7	9.1	-16.9	3.9
	jumping jack		0.68	14.0	21.0	-7.0	-4.5	3.4
			0.33	8.8	23.2	-14.4	-11.0	5.0
	jumping (full body)	jumps on both legs	0.91	8.6	29.8	-21.1	-0.5	6.6
			0.93	14.5	12.4	2.1	1.2	2.7
		jumps on left leg	0.21	6.2	9.7	-3.4	13.8	2.2
			0.45	12.5	23.7	-11.2	-0.2	6.0
		jumps on right leg	0.70	8.5	24.8	-16.2	4.7	4.1
			-0.35	14.8	16.1	-1.3	-7.5	5.8
	kicks and punches		0.29	30.4	58.3	-27.9	4.4	8.8
			0.33	23.5	43.6	-20.1	7.9	7.0
	running	big steps	0.24	13.7	27.6	-13.9	-9.5	6.3
			-0.11	15.2	27.2	-11.9	9.0	8.0
		small steps	0.50	6.3	28.1	-21.8	-2.4	8.6
			0.02	5.6	25.3	-19.6	-2.6	8.2

Table 77: Statistics of complex movements: Marker-based data compared to hybrid data of ankle plantar/dorsal flexion angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
forefoot	biking		0.98	42.7	51.6	-8.9	-5.1	3.3
			0.91	14.0	24.5	-10.5	1.7	3.5
	jumping (lower extremities)	jumps on both legs	0.91	49.1	46.0	3.1	7.3	6.3
			0.84	54.1	61.8	-7.7	6.6	10.8
		jumps on left leg	entire part has to be cut off					
			0.96	51.8	55.3	-3.5	7.6	8.0
		jumps on right leg	0.91	47.5	46.3	1.2	3.3	7.6
			0.47	5.2	14.1	-8.9	-3.0	3.4
		jumps on alternating legs	0.94	38.1	38.5	-0.4	7.2	4.9
			0.97	57.2	54.2	3.0	-2.6	7.2
	jumping jack		0.95	40.4	59.1	-18.7	-7.0	7.7
			0.94	47.8	56.6	-8.8	-5.4	5.6
	jumping (full body)	jumps on both legs	0.99	58.6	70.4	-11.8	-4.4	4.7
			0.98	61.8	70.8	-9.0	-5.0	3.7
		jumps on left leg	0.91	20.9	25.0	-4.0	-4.2	2.2
			0.96	59.4	71.1	-11.7	-3.5	4.8
		jumps on right leg	0.93	52.9	68.6	-15.7	-3.1	5.3
			0.76	20.2	24.0	-3.8	-9.1	5.5
	kicks and punches		0.86	81.6	69.6	12.0	8.1	7.8
			0.81	46.1	51.3	-5.2	7.6	5.5
	running	big steps	0.94	46.3	49.0	-2.7	3.6	3.4
			0.96	54.8	58.9	-4.1	-5.6	3.6
		small steps	0.92	20.7	23.5	-2.8	-0.4	2.7
			0.94	19.6	22.4	-2.9	-6.0	2.4
forefoot, heel	biking		0.99	42.7	42.1	0.5	-7.7	1.3
			0.95	14.0	17.3	-3.3	3.5	1.2
	jumping (lower extremities)	jumps on both legs	1.00	49.1	52.2	-3.1	-3.9	1.9
			0.99	54.1	54.7	-0.6	-0.4	2.5
		jumps on left leg	entire part has to be cut off					
			0.98	51.8	49.4	2.4	-10.9	3.6
		jumps on right leg	0.98	47.5	43.3	4.2	-4.8	3.5
			0.82	5.2	15.6	-10.4	4.1	2.6
		jumps on alternating legs	0.95	38.1	44.2	-6.1	1.9	2.1
			0.97	57.2	53.6	3.6	2.8	4.0
	jumping jack		0.99	40.4	46.5	-6.0	-19.1	2.0
			0.98	47.8	50.0	-2.3	-7.2	3.0

forefoot, heel	jumping (full body)	jumps on both legs	0.99	58.6	64.9	-6.3	0.5	2.6
			0.98	61.8	64.8	-3.0	-0.2	2.0
		jumps on left leg	0.95	20.9	24.6	-3.6	-7.9	1.3
			0.95	59.4	63.6	-4.2	-2.2	2.4
		jumps on right leg	0.96	52.9	63.2	-10.3	0.5	2.9
			0.90	20.2	22.8	-2.6	-10.1	3.6
	kicks and punches		0.89	81.6	63.4	18.1	-0.7	4.6
			0.91	46.1	41.7	4.5	3.7	4.0
	running	big steps	0.98	46.3	43.8	2.5	-2.2	2.2
			0.99	54.8	59.4	-4.6	1.5	1.9
		small steps	0.96	20.7	20.5	0.1	0.6	1.6
			0.94	19.6	19.9	-0.3	-3.7	1.9

Table 78: Statistics of complex movements: Marker-based data compared to hybrid data of ankle eversion/inversion angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	**Recording**		**Correlation**	**Angle range Motion [°]**	**Angle range Shape [°]**	**Angle range difference [°]**	**MV angle difference [°]**	**SD angle difference [°]**
lat. ankle	biking		0.37	5.3	2.7	2.7	19.9	1.7
			entire part has to be cut off					
	jumping (lower extremities)	jumps on both legs	0.44	21.7	6.5	15.2	-1.9	6.7
			entire part has to be cut off					
		jumps on left leg	0.19	3.2	13.7	-10.5	25.8	3.5
			0.64	12.8	18.0	-5.2	-11.6	4.1
		jumps on right leg	0.78	26.1	19.1	7.0	1.2	4.0
			entire part has to be cut off					
		jumps on alternating legs	0.02	22.7	18.5	4.3	0.9	8.2
			0.74	18.7	22.7	-4.0	-18.3	3.8
	jumping jack		0.14	38.4	15.9	22.5	-11.7	7.9
			0.44	21.1	15.8	5.3	9.7	5.0
	jumping (full body)	jumps on both legs	entire part has to be cut off					
			0.35	6.5	13.8	-7.2	-0.6	2.5
		jumps on left leg	-0.27	6.9	10.2	-3.3	9.7	3.4
			0.46	10.9	8.8	2.2	-1.0	2.3
		jumps on right leg	-0.10	6.6	5.6	1.0	3.8	3.1
			0.06	21.4	11.9	9.5	-7.8	6.6
	kicks and punches		0.46	23.6	24.4	-0.8	7.5	5.2
			0.29	31.0	22.2	8.8	-0.5	5.9
	running	big steps	0.56	14.0	26.3	-12.3	13.4	4.1
			0.34	10.8	19.4	-8.6	-8.2	3.4
		small steps	0.36	10.4	18.1	-7.7	9.3	4.9
			0.35	8.1	16.2	-8.2	-9.6	3.9

med. and lat. ankle	biking		-0.37	5.3	0.7	4.7	14.8	1.7
			entire part has to be cut off					
	jumping (lower extremi-ties)	jumps on both legs	0.93	21.7	16.7	5.0	3.4	4.0
			0.36	17.1	10.5	6.6	-12.0	3.5
		jumps on left leg	entire part has to be cut off					
			0.73	12.8	18.6	-5.8	-19.3	3.5
		jumps on right leg	0.85	26.1	20.7	5.4	-3.8	4.6
			entire part has to be cut off					
		jumps on alternating legs	0.15	22.7	8.9	13.8	13.6	6.1
			0.65	18.7	11.2	7.5	-11.3	3.9
	jumping jack		0.83	38.4	10.9	27.4	-9.0	6.9
			0.39	21.1	13.9	7.2	9.7	5.0
	jumping (full body)	jumps on both legs	entire part has to be cut off					
			0.05	6.5	13.1	-6.6	1.7	2.6
		jumps on left leg	0.38	6.9	7.8	-0.9	8.7	1.4
			-0.10	10.9	11.0	-0.1	0.7	3.7
		jumps on right leg	0.36	6.6	4.6	2.0	10.7	2.2
			0.30	21.4	4.3	17.1	0.5	5.3
	kicks and punches		0.68	23.6	28.2	-4.6	10.2	4.8
			0.34	31.0	19.5	11.5	-4.4	5.5
	running	big steps	0.61	14.0	14.0	0.0	9.9	2.8
			-0.04	10.8	14.8	-4.1	-4.4	4.5
		small steps	0.40	10.4	14.7	-4.3	8.5	3.7
			0.19	8.1	7.4	0.7	-0.3	2.5

Table 79: Statistics of complex movements: Marker-based data compared to hybrid data of ankle abduction/adduction angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	**Recording**		**Corre-lation**	**Angle range Motion [°]**	**Angle range Shape [°]**	**Angle range difference [°]**	**MV angle difference [°]**	**SD angle difference [°]**
lat. and med. knee	biking		0.97	10.5	9.3	1.2	-4.5	1.8
			0.64	16.0	12.2	3.7	-11.9	3.2
	jumping (lower extremi-ties)	jumps on both legs	0.67	9.4	35.6	-26.3	4.9	5.2
			0.80	12.7	27.2	-14.5	-25.9	5.2
		jumps on left leg	entire part has to be cut off					
			0.83	13.6	17.0	-3.5	-8.5	2.2
		jumps on right leg	0.56	11.1	15.6	-4.5	-3.5	3.6
			entire part has to be cut off					
		jumps on alternating legs	-0.11	10.5	29.5	-18.9	-13.4	8.7
			0.30	20.7	17.3	3.4	-15.8	6.3
	jumping jack		0.83	14.0	47.5	-33.5	-20.8	6.6
			0.13	8.8	26.9	-18.1	-5.9	7.2

lat. and med. knee	jumping (full body)	jumps on both legs	0.82	8.4	60.2	-51.7	11.5	18.6
			0.77	14.5	12.7	1.8	-0.4	2.6
		jumps on left leg	0.55	6.2	16.0	-9.8	7.8	3.7
			0.70	12.5	31.9	-19.4	3.0	7.5
		jumps on right leg	0.53	7.9	26.1	-18.2	-0.6	4.8
			-0.82	14.8	33.0	-18.2	-8.5	9.0
	kicks and punches		0.35	30.4	143.1	-112.7	4.9	12.7
			0.15	22.6	81.0	-58.4	10.0	18.4
	running	big steps	0.57	13.7	77.9	-64.2	4.1	24.1
			0.07	15.2	85.7	-70.4	-5.7	26.4
		small steps	0.63	6.3	19.3	-13.1	2.8	4.2
			-0.03	5.6	50.4	-44.9	-6.5	17.3
lat. and med. knee, forefoot	biking		1.00	10.5	9.9	0.6	-4.8	0.8
			0.64	16.0	11.2	4.8	-13.4	2.9
	jumping (lower extremi-ties)	jumps on both legs	0.86	9.4	29.9	-20.5	3.6	4.4
			0.94	12.7	22.8	-10.1	-15.4	3.4
		jumps on left leg	entire part has to be cut off					
			0.94	13.6	16.1	-2.5	-9.4	1.3
		jumps on right leg	0.79	11.1	16.5	-5.4	2.7	2.6
			entire part has to be cut off					
		jumps on alternating legs	0.05	10.5	21.8	-11.3	-9.1	5.5
			0.81	12.4	15.3	-2.8	0.6	1.7
	jumping jack		0.73	14.0	37.1	-23.1	-13.9	5.3
			0.01	8.8	29.0	-20.2	-13.7	9.1
	jumping (full body)	jumps on both legs	0.87	8.4	44.9	-36.4	7.1	11.7
			0.97	14.5	17.3	-2.8	0.9	1.9
		jumps on left leg	0.80	6.2	12.7	-6.5	6.7	2.8
			0.67	12.5	30.6	-18.1	2.3	7.7
		jumps on right leg	0.30	7.9	22.7	-14.8	2.3	4.7
			-0.48	14.8	26.9	-12.1	-4.9	7.0
	kicks and punches		0.28	30.4	53.7	-23.3	5.5	10.8
			0.36	22.6	59.6	-37.1	7.0	11.7
	running	big steps	0.58	13.7	79.5	-65.8	6.3	22.7
			0.17	15.2	81.0	-65.7	-3.8	22.6
		small steps	0.58	6.3	19.1	-12.8	2.6	4.6
			-0.14	5.6	32.4	-26.9	-5.3	11.5
lat. and med. knee, forefoot, heel	biking		1.00	10.5	6.1	4.3	0.3	1.3
			-0.29	16.0	6.8	9.2	-11.2	6.0
	jumping (lower extremi-ties)	jumps on both legs	0.75	9.4	21.3	-11.9	0.4	2.7
			0.89	12.7	10.7	2.1	-14.6	1.8
		jumps on left leg	entire part has to be cut off					
			0.49	13.6	9.4	4.1	-11.4	3.9

lat. and med. knee, forefoot, heel	jumping (lower extremities)	jumps on right leg	0.78	11.1	14.4	-3.4	4.0	2.5
			entire part has to be cut off					
		jumps on alternating legs	-0.10	10.5	17.1	-6.5	-7.4	5.6
			0.65	20.7	11.0	9.7	-16.6	4.7
	jumping jack		0.68	14.0	21.0	-7.0	-4.5	3.4
			0.26	8.8	17.3	-8.5	-10.5	4.2
	jumping (full body)	jumps on both legs	0.91	8.6	29.8	-21.1	-0.5	6.6
			0.93	14.5	12.4	2.1	1.2	2.7
		jumps on left leg	0.71	6.2	5.2	1.0	16.1	0.7
			0.42	12.5	23.7	-11.2	-0.7	5.8
		jumps on right leg	0.74	7.9	24.8	-16.9	4.2	4.4
			-0.66	14.8	15.5	-0.7	-8.9	6.5
	kicks and punches		0.36	30.4	62.0	-31.6	1.8	11.3
			0.27	22.6	43.6	-21.0	8.1	9.2
	running	big steps	0.24	13.7	27.6	-13.9	-9.5	6.3
			-0.14	15.2	27.2	-11.9	9.7	8.2
		small steps	0.25	6.3	26.1	-19.8	-4.6	8.0
			-0.25	5.6	22.2	-16.7	-3.0	8.4

Table 80: Statistics of complex movements: Marker-based data tracked in Simi Shape without silhouette-correspondences compared to hybrid data of ankle eversion/inversion angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	**Recording**		**Correlation**	**Angle range Motion [°]**	**Angle range Shape [°]**	**Angle range difference [°]**	**MV angle difference [°]**	**SD angle difference [°]**
lat. ankle	biking		entire part has to be cut off					
			entire part has to be cut off					
	jumping (lower extremities)	jumps on both legs	0.27	17.6	6.5	11.1	-10.9	5.5
			0.49	13.9	20.2	-6.4	-2.8	5.1
		jumps on left leg						
			0.79	12.9	18.0	-5.2	4.8	3.9
		jumps on right leg	0.91	6.5	15.1	-8.6	0.0	2.5
			entire part has to be cut off					
		jumps on alternating legs	0.90	14.9	23.1	-8.1	-9.1	3.9
			0.79	8.5	22.7	-14.2	-6.3	4.9
	jumping jack		0.11	6.0	10.2	-4.2	-3.1	3.0
			0.12	8.3	14.9	-6.6	1.8	4.0
	jumping (full body)	jumps on both legs	0.71	13.0	10.2	2.8	-3.1	2.5
			0.66	16.9	13.8	3.1	1.0	2.6
		jumps on left leg	-0.22	7.3	16.8	-9.6	5.5	4.6
			0.46	13.6	8.8	4.9	-1.8	4.0
		jumps on right leg	0.37	11.1	10.7	0.4	-4.5	3.5
			entire part has to be cut off					

lat. ankle	kicks and punches		0.72	25.5	25.9	-0.4	-3.4	4.1
			0.63	18.3	27.9	-9.5	0.6	5.0
	running	big steps	0.64	16.2	26.3	-10.1	6.4	3.4
			0.34	21.0	19.4	1.6	-2.8	4.8
		small steps	0.82	11.5	21.0	-9.5	2.8	2.9
			0.63	11.8	16.2	-4.4	-6.2	3.2
med. and lat. ankle	biking		entire part has to be cut off					
			entire part has to be cut off					
	jumping (lower extremi-ties)	jumps on both legs	0.91	17.6	16.7	1.0	-5.6	2.8
			0.77	13.9	10.5	3.3	1.0	3.0
		jumps on left leg	entire part has to be cut off					
			0.96	12.9	18.6	-5.8	-2.9	1.9
		jumps on right leg	0.91	6.7	20.7	-14.0	-4.2	3.9
			entire part has to be cut off					
		jumps on alternating legs	0.71	14.9	8.9	6.0	0.0	3.7
			0.83	8.5	9.2	-0.6	-0.5	1.8
	jumping jack		0.66	6.0	5.7	0.3	-0.9	1.3
			-0.17	8.3	12.1	-3.8	1.6	3.5
	jumping (full body)	jumps on both legs	0.92	13.0	9.3	3.7	-1.6	1.6
			0.94	16.9	14.1	2.8	0.3	2.3
		jumps on left leg	0.78	7.3	11.8	-4.5	3.9	1.5
			0.85	13.6	11.0	2.6	0.1	2.6
		jumps on right leg	0.69	11.1	11.0	0.1	0.3	2.1
			entire part has to be cut off					
	kicks and punches		0.81	25.5	28.8	-3.2	-0.5	4.1
			0.63	18.3	19.5	-1.1	-2.8	2.8
	running	big steps	0.78	16.2	14.0	2.2	2.7	2.2
			0.95	21.0	14.8	6.2	1.0	2.0
		small steps	0.84	11.5	15.3	-3.8	1.5	1.8
			0.96	11.8	7.4	4.4	3.1	1.5

Table 81: Statistics of complex movements: Marker-based data tracked in Simi Shape without silhouette-correspondences compared to hybrid data of ankle abduction/adduction angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	**Recording**		**Corre-lation**	**Angle range Motion [°]**	**Angle range Shape [°]**	**Angle range difference [°]**	**MV angle difference [°]**	**SD angle difference [°]**
lat. and med. knee	biking		0.93	6.4	7.7	-1.3	0.0	0.7
			-0.11	8.0	10.5	-2.4	-1.3	3.2
	jumping (lower extremi-ties)	jumps on both legs	0.85	22.8	35.6	-12.9	1.9	4.5
			0.90	11.3	27.2	-16.0	-12.9	4.9
		jumps on left leg	-0.44	7.4	3.7	3.7	-15.6	2.0
			0.26	9.1	14.5	-5.4	3.1	3.7

lat. and med. knee	jumping (lower extremities)	jumps on right leg	0.71	9.1	15.6	-6.5	-8.8	2.8
			entire part has to be cut off					
		jumps on alternating legs	0.95	19.7	32.3	-12.6	-3.8	4.0
			0.51	12.4	17.3	-4.9	0.6	2.8
	jumping jack		0.78	16.7	47.5	-30.8	-16.4	7.0
			0.89	21.9	41.5	-19.7	0.3	5.1
	jumping (full body)	jumps on both legs	0.93	27.1	60.2	-33.1	15.8	13.4
			0.90	17.6	12.7	4.9	1.3	1.9
		jumps on left leg	0.07	14.5	16.0	-1.5	-7.8	5.0
			0.91	27.3	31.9	-4.6	2.0	2.9
		jumps on right leg	0.68	26.4	26.1	0.3	-1.1	4.7
			0.35	12.0	33.0	-21.0	4.2	5.8
	kicks and punches		0.83	50.6	143.1	-92.5	-3.8	7.2
			0.76	45.7	81.0	-35.3	1.0	9.4
	running	big steps	0.93	34.2	77.9	-43.8	9.0	17.4
			0.98	33.5	85.7	-52.2	-12.7	19.9
		small steps	0.86	26.4	24.8	1.7	8.1	2.5
			0.89	26.1	54.2	-28.1	-6.8	10.7
lat. and med. knee, forefoot	biking		0.93	6.4	7.7	-1.3	0.2	1.3
			-0.11	8.0	10.5	-2.4	-2.4	4.0
	jumping (lower extremities)	jumps on both legs	0.93	22.8	29.9	-7.1	0.6	4.7
			0.92	11.3	22.8	-11.6	-2.4	3.7
		jumps on left leg	-0.01	7.4	10.2	-2.8	1.6	1.9
			0.37	9.1	16.1	-7.0	1.9	4.3
		jumps on right leg	0.78	9.1	16.5	-7.4	-2.5	2.5
			entire part has to be cut off					
		jumps on alternating legs	0.95	19.7	24.3	-4.6	-1.3	2.7
			0.81	12.4	15.3	-2.8	0.6	1.7
	jumping jack		0.72	16.7	37.1	-20.4	-9.5	5.4
			0.95	21.9	38.3	-16.4	-7.3	5.7
	jumping (full body)	jumps on both legs	0.94	27.1	47.2	-20.1	11.7	6.7
			0.92	17.6	17.3	0.3	0.3	2.3
		jumps on left leg	0.21	14.5	12.7	1.8	-10.0	4.4
			0.94	27.3	30.6	-3.3	1.5	2.0
		jumps on right leg	0.48	26.4	22.7	3.7	1.8	5.9
			0.65	12.0	26.9	-14.8	9.2	4.5
	kicks and punches		0.89	50.6	53.7	-3.1	-3.7	4.8
			0.84	45.7	59.6	-14.0	-1.1	5.0
	running	big steps	0.95	34.2	79.5	-45.4	11.3	16.2
			0.98	33.5	81.5	-48.0	-10.6	16.5
		small steps	0.80	26.4	19.1	7.3	8.5	4.3
			0.91	26.1	37.9	-11.8	-5.4	4.8
	biking		0.92	10.9	12.5	-1.7	-0.4	1.5
			0.93	11.7	7.7	3.9	-2.1	1.6

lat. and med. knee, forefoot	jumping (lower extremi-ties)	jumps on both legs	0.88	22.8	21.3	1.5	-2.5	1.4
			0.93	11.3	10.7	0.6	-1.6	1.2
		jumps on left leg	0.84	7.4	8.1	-0.7	-0.5	0.6
			0.95	9.1	9.4	-0.3	-1.1	0.8
		jumps on right leg	0.93	9.1	14.4	-5.4	-1.3	1.7
			entire part has to be cut off					
		jumps on alternating legs	0.98	19.7	20.8	-1.1	0.6	1.6
			0.75	12.4	11.0	1.4	-0.4	2.1
	jumping jack		0.91	16.7	21.0	-4.3	-0.2	2.2
			0.95	21.9	23.2	-1.3	-3.4	1.3
	jumping (full body)	jumps on both legs	0.99	27.1	29.8	-2.6	0.3	1.6
			0.95	17.6	12.4	5.2	0.6	1.7
		jumps on left leg	0.86	14.5	9.7	4.9	-4.7	1.6
			0.94	27.3	23.7	3.6	-1.2	2.4
		jumps on right leg	0.92	26.4	24.8	1.6	2.6	3.5
			0.93	12.0	16.1	-4.1	4.8	1.7
	kicks and punches		0.85	50.6	58.3	-7.7	-4.6	5.3
			0.88	45.7	43.6	2.1	-0.4	3.2
	running	big steps	0.94	34.2	27.6	6.6	-4.6	3.8
			0.93	33.5	27.2	6.3	5.4	3.8
		small steps	0.86	26.4	24.8	1.7	8.1	2.5
			0.9	26.1	25.3	0.8	-2.8	2.6

Table 82: Statistics of complex movements: Marker-based data compared to hybrid data of shoulder abduction/adduction angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
lat. elbow, triceps	biking		0.73	2.1	4.9	-2.9	4.6	0.9
			0.80	4.5	3.9	0.6	-3.8	1.0
	jumping (full body)	jumps on both legs	0.97	19.4	19.5	-0.1	0.1	1.5
			0.97	24.1	26.8	-2.7	0.7	2.2
		jumps on left leg	0.97	47.6	38.9	8.7	-0.5	3.1
			0.97	50.4	62.8	-12.3	1.2	4.5
		jumps on right leg	0.93	33.1	33.8	-0.6	-1.4	2.1
			0.98	51.4	46.6	4.8	-1.2	2.4
	kicks and punches		0.95	85.4	79.2	6.2	0.6	4.0
			0.95	101.2	79.6	21.6	4.5	6.5
	running	big steps	0.95	26.0	26.7	-0.8	-2.6	2.9
			0.59	10.9	10.1	0.8	-0.7	1.5
		small steps	0.95	14.9	15.2	-0.4	-0.5	1.3
			0.84	12.3	12.7	-0.5	3.9	1.5

Table 83: Statistics of complex movements: Marker-based data compared to hybrid data of shoulder rotation angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
triceps	biking		0.89	3.1	97.3	-94.2	-42.0	9.1
			0.18	6.3	5.9	0.4	34.4	2.3
	jumping (full body)	jumps on both legs	0.97	58.5	54.0	4.5	-17.3	3.7
			0.94	46.3	51.2	-5.0	18.6	2.2
		jumps on left leg	0.73	64.2	86.5	-22.3	-13.2	14.3
			0.89	94.7	120.0	-25.4	17.5	10.9
		jumps on right leg	0.49	99.9	124.6	-24.7	-5.8	20.7
			0.89	54.0	62.6	-8.6	23.3	6.8
	kicks and punches		0.89	142.8	154.1	-11.3	-15.7	12.6
			0.92	113.3	181.5	-68.2	12.3	17.1
	running	big steps	0.88	27.3	39.1	-11.8	-15.8	4.3
			0.95	20.2	34.6	-14.4	46.3	4.8
		small steps	0.93	15.6	17.0	-1.4	-20.4	2.2
			0.91	14.7	14.1	0.7	30.1	1.7
lat. elbow, triceps	biking		0.08	3.1	96.5	-93.4	-41.9	9.1
			0.34	6.3	6.3	-0.1	33.3	1.7
	jumping (full body)	jumps on both legs	0.98	58.5	53.9	4.6	-19.0	1.8
			0.92	46.3	46.8	-0.5	15.6	2.1
		jumps on left leg	0.99	64.2	61.2	3.1	-19.2	2.6
			0.91	94.7	74.0	20.7	8.2	9.3
		jumps on right leg	0.98	99.9	91.1	8.8	-17.4	5.3
			0.96	54.0	55.7	-1.7	14.6	3.1
	kicks and punches		0.95	144.8	114.0	30.8	-17.5	10.0
			0.89	113.3	126.2	-12.9	12.3	15.1
	running	big steps	0.90	27.3	32.1	-4.8	-18.7	3.5
			0.99	20.2	24.2	-4.0	42.4	1.8
		small steps	0.98	15.6	19.0	-3.5	-20.1	1.6
			0.94	14.7	14.7	0.0	29.9	1.6

Table 84: Statistics of complex movements: Marker-based data compared to hybrid data of shoulder abduction/adduction angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
lat. elbow, triceps	biking		entire part has to be cut off					
			entire part has to be cut off					
	jumping (full body)	jumps on both legs	0.97	19.4	19.5	-0.1	0.1	1.5
			0.97	24.1	26.8	-2.7	0.7	2.2
		jumps on left leg	0.97	47.6	38.9	8.7	-0.5	3.1
			0.97	50.4	62.8	-12.3	1.2	4.5
		jumps on right leg	0.93	33.1	33.8	-0.6	-1.4	2.1
			0.98	51.4	46.6	4.8	-1.2	2.4
	kicks and punches		0.95	85.4	79.2	6.2	0.6	4.0
			0.95	101.2	79.6	21.6	4.5	6.5
	running	big steps	0.95	26.0	26.7	-0.8	-2.6	2.9
			0.83	10.8	10.1	0.7	-0.5	1.4
		small steps	0.95	14.9	15.2	-0.4	-0.5	1.3
			0.84	12.3	12.7	-0.5	3.9	1.5

Table 85: Statistics of complex movements: Marker-based data compared to hybrid data of shoulder rotation angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
triceps	biking		entire part has to be cut off					
			entire part has to be cut off					
	jumping (full body)	jumps on both legs	0.97	58.5	54.0	4.5	-17.3	3.7
			0.94	46.3	51.2	-5.0	18.6	2.2
		jumps on left leg	0.73	64.2	86.5	-22.3	-13.2	14.3
			0.89	94.7	120.0	-25.4	17.5	10.9
		jumps on right leg	0.49	99.9	124.6	-24.7	-5.8	20.7
			0.89	54.0	62.6	-8.6	23.3	6.8
	kicks and punches		0.89	142.8	154.1	-11.3	-15.7	12.6
			0.92	113.3	181.5	-68.2	12.3	17.1
	running	big steps	0.88	27.3	39.1	-11.8	-15.8	4.3
			0.95	20.2	34.6	-14.4	46.3	4.8
		small steps	0.93	15.6	17.0	-1.4	-20.4	2.2
			0.91	14.7	14.1	0.7	30.1	1.7

lat. elbow, triceps	biking		entire part has to be cut off					
			entire part has to be cut off					
	jumping (full body)	jumps on both legs	0.98	58.5	53.9	4.6	-19.0	1.8
			0.92	46.3	46.8	-0.5	15.6	2.1
		jumps on left leg	0.99	64.2	61.2	3.1	-19.2	2.6
			0.91	94.7	74.0	20.7	8.2	9.3
		jumps on right leg	0.98	99.9	91.1	8.8	-17.4	5.3
			0.96	54.0	55.7	-1.7	14.6	3.1
	kicks and punches		0.95	144.8	114.0	30.8	-17.5	10.0
			0.89	113.3	126.2	-12.9	12.3	15.1
	running	big steps	0.90	27.3	32.1	-4.8	-18.7	3.5
			0.99	20.2	24.2	-4.0	42.4	1.8
		small steps	0.98	15.6	19.0	-3.5	-20.1	1.6
			0.94	14.7	14.7	0.0	29.9	1.6

Table 86: Statistics of complex movements: Marker-based data compared to hybrid data of elbow flexion/extension angles including parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Correlation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
triceps	biking		0.81	8.0	19.2	-11.2	12.6	2.0
			0.25	3.6	5.3	-1.7	10.7	1.1
	jumping (full body)	jumps on both legs	0.93	33.8	33.8	0.0	-14.3	3.0
			0.90	21.8	25.5	-3.7	-1.7	1.9
		jumps on left leg	0.87	56.6	77.7	-21.1	6.8	10.5
			0.96	73.7	91.5	-17.8	1.8	8.6
		jumps on right leg	0.75	59.8	88.9	-29.1	0.7	12.4
			0.76	72.4	88.9	-16.5	1.4	7.6
	kicks and punches		0.90	113.8	130.0	-16.2	-6.4	10.3
			0.87	115.7	133.2	-17.5	-0.5	7.1
	running	big steps	0.97	31.6	30.5	1.1	-14.5	1.8
			0.70	17.7	21.5	-3.7	-5.1	3.1
		small steps	0.93	33.8	33.8	0.0	-14.3	3.0
			0.90	21.8	25.5	-3.7	-1.7	1.9
lat. elbow, triceps	biking		0.89	8.0	18.8	-10.8	12.4	1.9
			0.39	3.6	5.2	-1.6	8.6	0.9
	jumping (full body)	jumps on both legs	0.93	33.8	37.4	-3.5	-20.2	4.1
			0.92	21.8	22.7	-0.9	-4.4	1.3
		jumps on left leg	0.95	56.6	78.5	-22.0	3.0	5.9
			0.99	73.7	88.3	-14.5	-11.6	4.7
		jumps on right leg	0.89	59.8	79.9	-20.1	-4.6	7.5
			0.88	72.4	78.2	-5.8	-12.3	5.6

lat. elbow, triceps	kicks and punches		0.94	113.8	117.4	-3.6	-5.5	7.8
			0.89	115.7	116.4	-0.7	-6.2	8.4
	running	big steps	0.97	31.6	31.2	0.4	-14.7	1.8
			0.72	17.7	31.5	-13.8	-11.2	3.7
		small steps	0.93	33.8	37.4	-3.5	-20.2	4.1
			0.92	21.8	22.7	-0.9	-4.4	1.3
lat. elbow, triceps, lat. and med. wrist	biking		0.88	8.0	17.8	-9.7	12.9	1.7
			0.49	3.6	3.0	0.6	12.6	0.8
	jumping (full body)	jumps on both legs	0.95	66.7	78.9	-12.2	5.6	3.9
			0.90	87.8	101.9	-14.1	-6.4	7.2
		jumps on left leg	0.98	56.6	79.4	-22.8	8.0	7.9
			0.99	73.7	94.4	-20.7	-6.9	5.5
		jumps on right leg	0.91	59.8	62.4	-2.6	-0.3	4.0
			0.94	72.4	88.7	-16.4	2.8	7.2
	kicks and punches		0.96	113.8	113.7	0.1	-14.7	6.4
			0.97	115.7	118.6	-2.9	6.8	3.8
	running	big steps	0.98	31.6	31.8	-0.2	-7.2	1.4
			0.73	17.7	14.4	3.3	-6.8	2.5
		small steps	0.97	33.8	31.0	2.8	-15.1	1.9
			0.93	21.8	17.1	4.7	-4.0	2.4

Table 87: Statistics of complex movements: Marker-based data compared to hybrid data of elbow flexion/extension angles excluding parts with small ranges of motion. The first row of each recording and marker combination presents values of the right body side, the second row values of the left body side.

Markers	Recording		Corre-lation	Angle range Motion [°]	Angle range Shape [°]	Angle range difference [°]	MV angle difference [°]	SD angle difference [°]
triceps	biking		0.83	5.9	5.5	0.4	11.4	0.8
			entire part has to be cut off					
	jumping (full body)	jumps on both legs	0.93	33.8	33.8	0.0	-14.3	3.0
			0.90	21.8	25.5	-3.7	-1.7	1.9
		jumps on left leg	0.87	56.6	77.7	-21.1	6.8	10.5
			0.96	73.7	91.5	-17.8	1.8	8.6
		jumps on right leg	0.74	59.8	88.9	-29.1	-0.9	14.0
			0.85	72.4	88.9	-16.5	1.0	8.4
	kicks and punches		0.90	113.8	130.0	-16.2	-6.4	10.3
			0.86	115.7	133.2	-17.5	-0.7	7.2
	running	big steps	0.97	31.6	30.5	1.1	-14.5	1.8
			0.70	17.7	21.5	-3.7	-5.1	3.1
		small steps	0.93	33.8	33.8	0.0	-14.3	3.0
			0.90	21.8	25.5	-3.7	-1.7	1.9
lat. elbow, triceps	biking		1.00	5.9	6.1	-0.2	11.8	0.2
			entire part has to be cut off					

lat. elbow, triceps	jumping (full body)	jumps on both legs	0.93	33.8	37.4	-3.5	-20.2	4.1
			0.92	21.8	22.7	-0.9	-4.4	1.3
		jumps on left leg	0.95	56.6	78.5	-22.0	3.0	5.9
			0.99	73.7	88.3	-14.5	-11.6	4.7
		jumps on right leg	0.85	59.8	79.9	-20.1	-7.5	6.7
			0.92	72.4	78.2	-5.8	-13.0	6.2
	kicks and punches		0.94	113.8	117.4	-3.6	-5.5	7.8
			0.88	115.7	116.4	-0.7	-6.6	8.4
	running	big steps	0.97	31.6	31.2	0.4	-14.7	1.8
			0.72	17.7	31.5	-13.8	-11.2	3.7
		small steps	0.93	33.8	37.4	-3.5	-20.2	4.1
			0.92	21.8	22.7	-0.9	-4.4	1.3
lat. elbow, triceps, lat. and med. wrist	biking		1.00	6.1	5.8	0.2	12.6	0.1
			entire part has to be cut off					
	jumping (full body)	jumps on both legs	0.95	66.7	78.9	-12.2	5.6	3.9
			0.90	87.8	101.9	-14.1	-6.4	7.2
		jumps on left leg	0.98	56.6	79.4	-22.8	8.0	7.9
			0.99	73.7	94.4	-20.7	-6.9	5.5
		jumps on right leg	0.91	59.8	62.4	-2.6	-0.3	4.0
			0.94	72.4	88.7	-16.4	2.8	7.2
	kicks and punches		0.96	113.8	113.7	0.1	-14.7	6.4
			0.97	115.7	118.6	-2.9	6.8	3.8
	running	big steps	0.98	31.6	31.8	-0.2	-7.2	1.4
			0.73	17.7	14.4	3.3	-6.8	2.5
		small steps	0.97	33.8	31.0	2.8	-15.1	1.9
			0.93	21.8	17.1	4.7	-4.0	2.4

Declaration of Authorship

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