Wearable Motion Capture System Evaluation for Biomechanical Studies for Hip Joints

Senay Mihcin
Mechanical Engineering Department,
Izmir Institute of High Technology,
Izmir 35620, Turkey
e-mail: senaymihcin@iyte.edu.tr

Samet Ciklacandir
Biomedical Engineering,
Izmir Katip Celebi Universitesi,
Izmir 35620, Turkey
e-mail: samet.cikla@gmail.com

Mertcan Kocak
Mechatronics Department,
Izmir Katip Celebi Universitesi,
Izmir 35620, Turkey
e-mail: mertcan.kocak@ikcu.edu.tr

Aliye Tosun
Izmir Ataturk Research and Training Hospital,
Izmir 35620, Turkey
e-mail: tosunaliye@yahoo.com

Human motion capture (MOCAP) systems are vital while determining the loads occurring at the joints. Most of the clinical MOCAP systems are very costly, requiring investment and infrastructure. Therefore, alternative technologies are in demand. In this study, a novel markerless wearable MOCAP system was assessed for its compatibility with a biomechanical modeling software. To collect evidence, experiments were designed in two stages for quantifying the range of motion (ROM) of the hip joint, in vitro and in vivo. Three constrained single-plane motions—abduction/adduction, flexion/extension, and internal/external rotation movements of the active leg—were analyzed. The data were collected from 14 healthy volunteers, using the wearable system and a medical grade optoelectronic MOCAP system simultaneously and compared against. For the in vitro study, the root-mean-square error (RMSE) for the abduction/adduction motion of the hip joint was calculated as 0.11 deg/0.30 deg and 0.11 deg/0.09 deg, respectively, for the wearable and the opto-electronic system. The in vivo Bland–Altman plots showed that the two system data are comparable. The simulation software is found compatible to run the simulations in offline mode. The wearable system could be utilized in the field of biomechanics software for running the kinetic simulations. The results demonstrated that the wearable system could be an alternative in the field of biomechanics based on the evidence collected. [DOI: 10.1115/1.4049199]

Keywords: MOCAP, motion analysis, human motion capture systems, lower body, wearable MOCAP, verification, validation, ISO13485

1 Introduction

Motion capture (MOCAP) allows human movements to be captured for further analysis by collecting data from the analog world to simulate it in the digital environment [1]. In this technique, behaviors of the objects are obtained from the captured data [2]. MOCAP could be defined as the analysis of a scene, which results in mathematical formulation of the motion provided by the human subjects. Today, MOCAP is widely utilized in medicine [3], sports [4], entertainment [5], law/surveillance [6], and also in the design of ergonomic environments [7–9].

Motion capture systems can provide comprehensive data, which define the three-dimensional (3D) marker trajectory, displacement, angular and linear velocity, and acceleration of the limps. These comprehensive data are used heavily in animation industry, life sciences, or in the field of engineering applications. These data are crucial especially, while deriving kinematic, kinetic information, understanding the role of soft tissues such as the activity pattern of the muscles in different applications as in clinical gait analysis [10], musculoskeletal modeling [11], and in the field of biomechanics. Laboratory-based 3D motion capture methods are mostly utilized in hospitals, and research environments. However, there is limited availability as they require investment for infrastructure, maintenance, process time, and resources for qualified personnel to run the laboratories [12]. Lab-based MOCAP systems have their own disadvantages such as the difficulty of simulating the daily life activities in the laboratory conditions [13]. Due to these challenges, there is an unmet need requiring the development of a new MOCAP system and algorithm that might provide the required answers.

Inertial motion capture (IMC) systems are designed to provide an evaluation of the orientation for the segments and the full-body MOCAP in the absence of laboratory conditions [14]. IMC systems do not require the line of sight to capture the data. An IMC system (Xsens Awinda, Xsens Technologies BV, Enschede, The Netherlands) was shown to predict joint angles with a good accuracy [15] and used to calculate the 3D reaction forces and the joint moments during gait with a comparable accuracy to the optical motion prediction [16]. However, one of the limitations of this IMC system was its cost. Especially, in the countries with limited resources to conduct research, and design experiments, it is very important to have an affordable system. There is still an unmet need for a system, which is affordable, reliable, and easy to run and use with less process time to enable the implementation of evidence-based patient treatment methods globally.

Analysis of human motion in the medical field is very important to understand the movements of the joints in the body. In order to determine the appropriate treatment methods before the surgery, the gait analyses supported by MOCAP systems are key to successful interventions and operations in the medical field. Therefore, it is very important to have a medical grade MOCAP system, which can be relied on for the welfare of the patients. With the established hardware technology in the digital entertainment, art and media fields, having user friendly graphical interfaces for data collection, already available wearable MOCAP systems, with affordable prices, could be considered as an alternative solution. But, in the field of health and medicine, for quality assurance purposes, it is required to provide evidence for the fitness of the system for its intended use [17]. International Organization for Standardization (ISO) 13485 details the requirements for a broad quality management system for the design and for the manufacture of the medical devices. As a part of this qualification process, it is important to produce evidence, demonstrating the fitness of the device according to the specifications, set initially, according to which, the system should perform. This is usually achieved by comparing the new system's performance against an already available CE marked product with similar intended use.

In this study, we are proposing that the MOCAP system, which is normally used in animation industry, could be utilized as an affordable option to investigate the lower body kinematics with a biomechanics software, in the field of biomechanics. The study is designed in two stages, mainly in vitro and in vivo by comparing the wearable suit against an optoelectronic MOCAP system, which is already qualified for medical use. The successful transfer of the collected data into a biomechanics software is checked for

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the system to be utilized widely by the research personnel, mostly by M.Sc. and Ph.D. students to conduct research in this field.

2 Materials and Methods

In order to evaluate the fitness of a wearable marker-less MOCAP system, SMARTSUIT PRO (Rokoko, Copenhagen, Denmark) in combination with an in silico human modeling software package "BIOMECHANICS OF BODIES" (BoB, Coventry, UK) for lower body kinematics, against an optoelectronic MOCAP system, OptiTrack Flex-3 (LEYARD, Corvallis, OR) was utilized. The results were compared with each other after collecting data from the both systems simultaneously.

2.1 Materials. The novel wearable MOCAP system, SMARTSUIT PRO (Rokoko), which is to be tested for its suitability for the lower body, has 19 sensors. Each of these sensors has 9 degree-of-freedom (DoF). These 19 inertial measurement units are connected to each other with custom made cables, connecting to a hub providing the wireless communication (Fig. 1) with the computer. The sensors are placed into the hidden pockets inside the suit. The suit itself, is a high performance, durable nylon based fabric. For the suit to fit all body types, around the sensors, adjustable straps are tightened to prevent relative motion between the limb and the sensors. Inside the suit, there are seamlessly integrated tunnels. These tunnels protect the cables, as well as the sensors without restricting the motion of the subjects. The hub contains a USB 2.0 communication on board memory and also a smart home button for one-person to be able to handle the recording. The WiFi is able to transfer data within a 100 m distance. The data transfer is in real-time. The data transfer rate is 100 frames per second (fps). The suit has a software package called, SMARTSUIT STUDIO, to monitor the action in real-time in silico. The SMARTSUIT STUDIO's Graphical User Interface (GUI) is user friendly and one can intuitively follow the procedures to record the motion in real-time. The STUDIO software can run on a Windows platform. The suit has a 6 h battery time, allowing longer motion scenarios to be completed, if required.

To compare the results of SMARTSUIT PRO, another system, which is utilized in gait labs for medical purposes, was selected. The selected system, OptiTrack Flex-3 (LEYARD), is widely utilized in the field as a gold standard, consisting of marker sets and multiple cameras (Fig. 2). With OptiTrack Flex-3, according to the type of motion, specific number of marker sets and also a number of cameras are utilized. OptiTrack has a reputation for its processing capability and precision. It is possible to gather marker data down to submillimeter levels with high level of accuracy. The data sampling rate of OptiTrack Flex-3 system is 100 Hz [18–20]. The OptiTrack System that we used in our experiment had six Flex3 cameras (Fig. 2), and passive markers. The system has a dedicated software called "Motive" providing a graphical user interface for controlling the markers during the data acquisition process. Before recording the data, all required checks are completed to control if there are any obstacles causing a line of sight problem for the markers a trained personnel was utilized to complete the data acquisition procedure.

For the proof-of-concept part of the study, an in vitro experimental setup was designed. Three constrained single-plane motions, abduction/adduction, flexion/extension, and internal/external rotation movements, of the hip joined were planned to be inspected. For this reason, based on the dimensions of a female, 5th percentile (3B Scientific) model, polylactic acid (with negligible weight) leg mimicking limb, printed using a 3D printer, was attached to a servomotor (MG 995), representing the hip joint (Fig. 3). The servomotor was confined to provide a single-plane motion to control the rotation in one axis only and have a predefined true range of motion (ROM) value for the analyses. The rotations were controlled with an Arduino Uno Board. The motor was supplied by TT Technic MCH 303D DC power supply. The range of motion for each set of motions is provided in Table 1 [21].

2.2 Subjects. To be able to conduct experiments on healthy volunteers, ethics committee permission was obtained successfully from the medical faculty of the university. The experiment and the aim of the study were explained to each participant demonstrating the set of motions that they were required to perform. Each volunteer signed an informed consent form before the data collection procedure began. 14 healthy individuals volunteered for this study. The volunteers had no previous history of lower body injuries. These volunteers were chosen randomly. Most of the volunteers were M.Sc. and Ph.D. students with an average age of 25±7.2 years, average height of 172±9.3 cm, and average weight of 75±14.2 kg, consisting of seven males and seven females.

2.3 Procedure. Initially, in vitro proof-of-concept study was completed. This involved collecting data from the in vitro setup using the SMARTSUIT PRO-and OptiTrack Flex-3 system simultaneously. The root-mean-square errors (RMSEs) were calculated by estimating the difference between the controlled range of motion and the measured range of motion by the two systems. To ensure that the in vitro setup produces the desired range of motion, the system was controlled and calibrated before the experiments. Bland–Altman graphs were drawn to check if SMARTSUIT PRO can produce replaceable data with that of OptiTrack Flex-3 system.

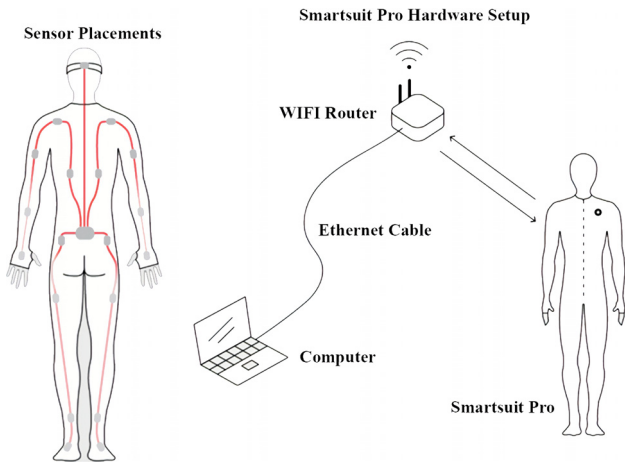

Fig. 1 SMARTSUIT PRO suit itself on the left, showing the configuration of sensors over the suit and on the right the full configuration of the system showing the communication with the computer using the WIFI

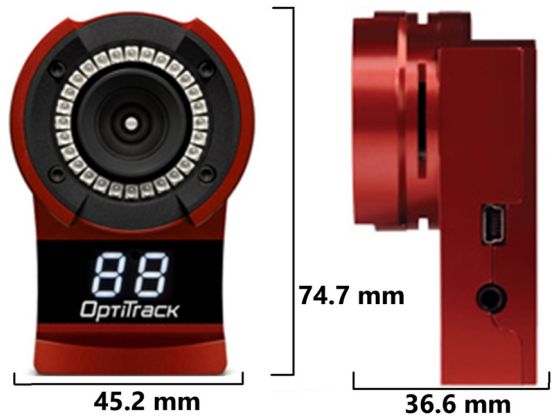

Fig. 2 OptiTrack camera system which uses markers to detect the motion of the limb (Flex3 Camera dimensions)

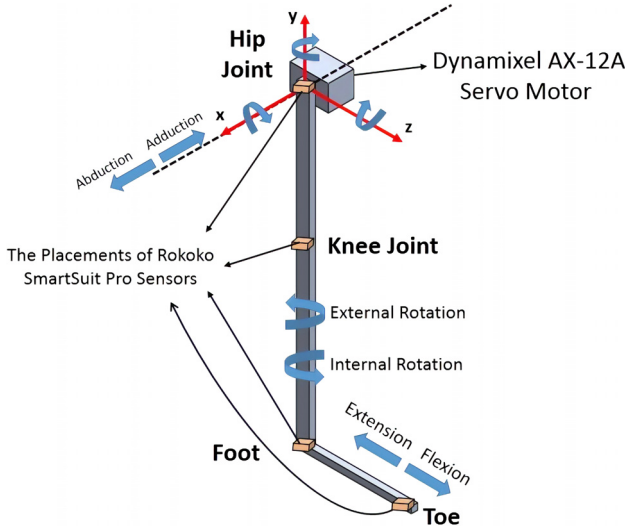

Fig. 3 Schematic model of the leg limb showing hip rotation for each fully constrained single plane

Based on the successful evidence, the second stage of the study, in vivo part, was planned. For the in vivo part, before the experiment, the subjects were asked to wear the suit. The straps at the sensor locations were secured for no relative motion to occur between the skin and the straps. The markers for OptiTrack Flex-3 system were placed at the same location of the inertial measurement unit sensors of the SMARTSUIT PRO.

The normal range of motion for the hip flexion is expected to be 130 deg as shown in Fig 4(*a*) with no bending at the knee location. The joint angles of interest for this study were the angles between the hip (measured between the neutral location and the current location) for the calculation of flexion/extension ROM in the sagittal plane. In the coronal plane (Fig. 4(*b*)), abduction/adduction ROM, and in the transverse plane (Fig. 4(*c*)), internal/external rotation ROM were measured. All the movements were shown to volunteers (Fig. 4) before they were asked to repeat the movements (abduction, flexion, and rotations) themselves. The subjects were asked to repeat the motion three times, in three sets of motion to form the data sets. To collect data simultaneously using OptiTrack Flex-3, the markers were placed over the subjects at the same locations with the sensors of SMARTSUIT PRO. The start command was given to the operators to start recording the data. With the successful collection of data, statistical analyses were completed to compare the consistency of SMARTSUIT PRO data with that of OptiTrack system.

3 Methodology

3.1 Proof of Concept. The hip flexion/extension, abduction/adduction, and internal/external rotation motion were performed on the skeletal model. The sensors were placed over the skeleton model for the inspected leg and the rest of the skeleton, wearing the suit over. During the motion, both SMARTSUIT PRO-and OptiTrack Flex-3 were in the record mode. To find the hip angle, two vectors were constructed (Fig. 5). The vector A in the image shows the maximum position during the abduction motion of the joint, while the vector B defines the stationary position of the leg. The joint between these two points represents the abduction angle as represented in the frontal view of the human figure (Fig. 5). While calculating the abduction, adduction, flexion, extension angles, and the hip and toe sensors were used. A vector was created between the hip and the toe sensors (Eq. (1)). The other position vector (vector B Eq. (2)) was also defined with 3D coordinates obtained from sensor data. Tangent value of the angle (Eq. (5)) was calculated by dividing the cross product (Eq. (4)) by the dot product (Eq. (3)). Using the arc tangent trigonometric

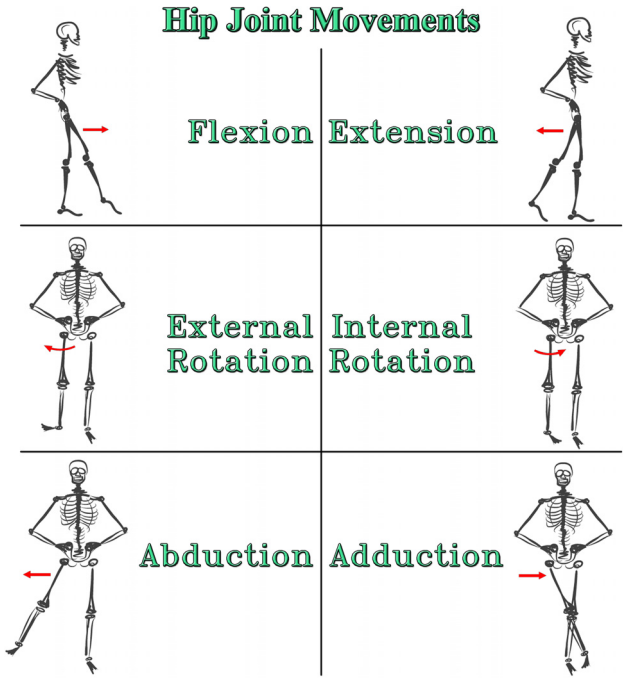

Fig. 4 (*a*) Single joint movements of hip flexion/extension, (*b*) abduction/adduction, (*c*) internal/external rotation is demonstrated starting with the leg in neutral position bringing the leg to the extreme level for ROM to be assessed

function, the angle in between was calculated. The rotation angle was calculated by creating vectors with the help of toe, foot, and toe tip sensors using the same formulas for the internal–external rotation calculations

$$\mathbf{OA} = (x_a - x_o,\ y_a - y_o, z_a - z_o) \tag{1}$$

$$\mathbf{OB} = (x_b - x_0,\ y_b - y_0,\ z_b - z_o) \tag{2}$$

$$\mathbf{AB} = |OA|.|OB|\cos\alpha \tag{3}$$

$$\mathbf{A} \times \mathbf{B} = A.B\sin\alpha \tag{4}$$

$$\tan\alpha = \frac{\mathbf{A} \times \mathbf{B}}{\mathbf{A}.\mathbf{B}} \tag{5}$$

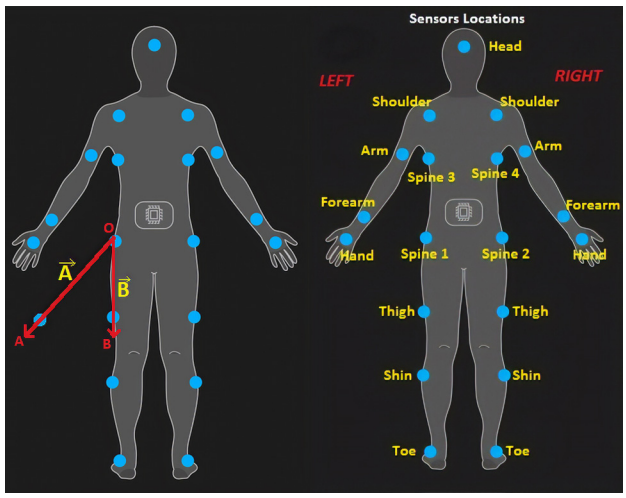

Fig. 5 Schematic view for definition of vectors, and markers attached to the suit over human anatomical land marks

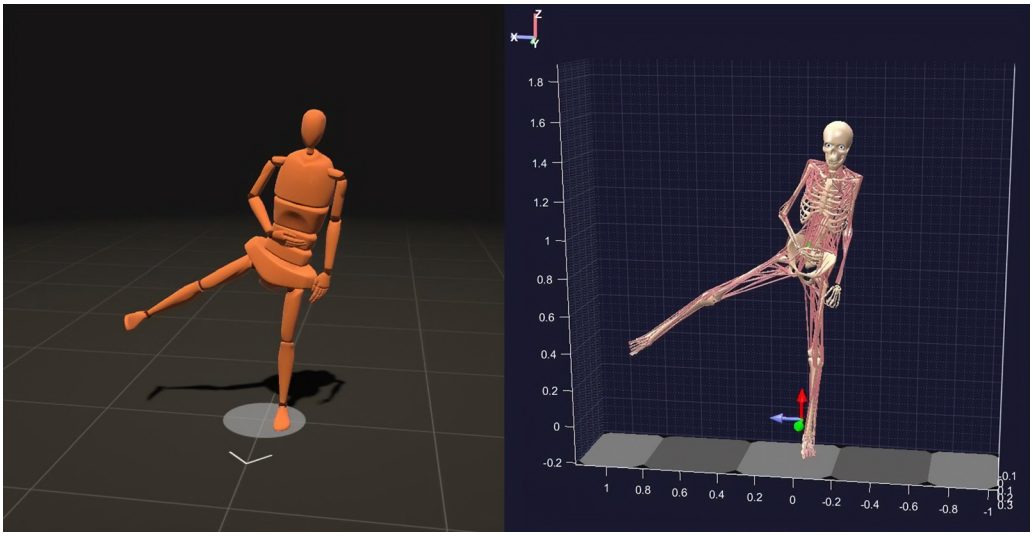

Fig. 6 Offline BoB simulation output on using the data collected by SMARTSUIT PRO on the left, and SMARTSUIT PRO real-time interface on the right

4 Experimental Results

The data files were recorded. They were converted into CSV file format to feed data into the BIOMECHANICS OF BODIES (BoB) module, which works in MATLAB (v2018b, MathWorks, Natick, MA). The offline data were simulated in BoB as shown in Fig. 6. BoB can calculate the joint angles and reaction forces for more complex biomechanical analysis. The data format is proven to be compatible replicating the same motion as shown in GUI of BoB and software of SMARTSUIT PRO (Fig. 6).

We calculated the angle using our MATLAB code using the data obtained via both OptiTrack Flex-3 and SMARTSUIT PRO. The RMSE value for each system was calculated against the ROM values provided in Table 1. For the in vitro study, the RMSE for the abduction/adduction motion of the hip joint was calculated as 0.11 deg/0.30 deg and 0.11 deg/0.09 deg, respectively, for the SMARTSUIT PRO-and the OptiTrack Flex-3 system with a Pearson coefficient of 0.8/0.9, for flexion/extension as 0.6 deg/0.1 deg and 0.18 deg/0.26 deg, respectively, with a Pearson coefficient of 0.92/0.90, for internal/external rotation as 0.25 deg/0.25 deg and 0.09 deg/0.15 deg, respectively, with a Pearson coefficient of 0.85/0.98 as shown in Table 2. Bland–Altman graphs showed that both systems produce comparable data with each other based on the data collected from the in vitro setup (Fig. 7).

in vivo RMSE between the SMARTSUIT PRO-and the OptiTrack Flex-3 system for abduction/adduction was 1.52 deg/1.53 deg and with Pearson coefficient of 0.99/0.98, for flexion/extension, the calculated RMSE was 1.38 deg/1.81 deg with Pearson coefficient of 0.99/0.98 for the internal/external rotation, the RMSE was 1.61 deg/1.53 deg with Pearson coefficient of 0.99/0.99, respectively, (Table 3). Bland–Altman graphs showing the limits of agreement between the two systems using the in vivo data are

Table 1 Range of motion of hip joint in each single plane for each motion type

Motion type	ROM in angles
Abduction/adduction	50 deg/30 deg
Flexion/extension	130 deg/20 deg
Internal/external rotation	40 deg/30 deg

Table 2 The in vitro result of RMSE values and Pearson correlation coefficient between the two systems. For hip flexion/extension, abduction/adduction, internal/external rotations using the dataset collected by SMARTSUIT PRO-and OptiTrack with three repetitions

In vitro	RMSE for each system		
Motion type	SMARTSUIT PRO	OptiTrack	Pearson correlation
Abduction	0.11	0.11	0.80
Adduction	0.30	0.09	0.90
Flexion	0.60	0.18	0.92
Extension	0.10	0.26	0.90
Internal rotation	0.25	0.09	0.85
External rotoation	0.25	0.15	0.98

Table 3 The in vivo result of RMSE values and Pearson Correlation Coefficient between the two systems for hip flexion/extension, abduction/adduction, and internal/external rotations using the dataset collected by SMARTSUIT PRO-and OptiTrack Flex-3 with three repetitions

In vivo	RMSE	Pearson
Abduction	1.52	1.00
Adduction	1.53	0.98
Flexion	1.38	1.00
Extension	1.81	0.99
Internal rotation	1.61	0.99
External rotation	1.53	0.99

Table 4 Numeric angular values showing the deviation from the zero value in B-A graphs with corresponding upper limit and lower limit values

In vivo	In degrees		
Motion type	Bias	Upper limits of agreement	Lower limits of agreement
Abduction	−0.6	2.1	−3.4
Adduction	−0.2	2.8	−3.2
Flexion	−0.3	2.3	−3
Extension	−0.4	2.2	−2.9
Internal rotation	−0.6	2.5	−3.6
External rotation	−0.7	2	−3.4

shown in Fig. 8, also providing numerical details in Table 4 for bias, upper and lower limits of agreement in degrees.

5 Discussion

In this study, our aim is to provide evidence for an already available MOCAP system, which is currently used in animation industry in order to use it in the field of biomechanics as a medical device. For this reason, the study consisted of a carefully planned two-stage approach. Human population might have different range of motion values even for a well-defined activity, flexion/extension, adduction/abduction, and internal/external rotations, which might vary from person to person. To be able to eliminate subjective differences and eliminate the effect of combined motion scenarios, in vitro step was designed. The data were collected using SMARTSUIT PRO-and OptiTrack MOCAP systems simultaneously. The in vitro setup was controlled with a step motor simulating the ROM values of the hip joint. This input datum was treated as a true value for both of the systems so that we were able to provide evidence for the accuracy of both systems providing RMSE values. The RMSE values were less than 1 deg for both of the systems. This was convincing enough and provided required evidence for us to be able to carry on with the volunteer experiments. With this evidence, it was possible to obtain ethics approval for us to collect data from healthy volunteer population. Pearson correlation coefficient was calculated only to show that there is a linear relationship between the readings of both systems [22]; this means, if OptiTrack readings tend to increase, then there is a similar trend in the readings of SMARTSUIT PRO. For in vitro results, Pearson values were between 0.8 and 0.98, indicating linear tendency between the systems. However, one should keep in mind that this does not mean the agreement between the systems; instead, Bland–Altman graphs are utilized to provide evidence for limits of agreement [22].

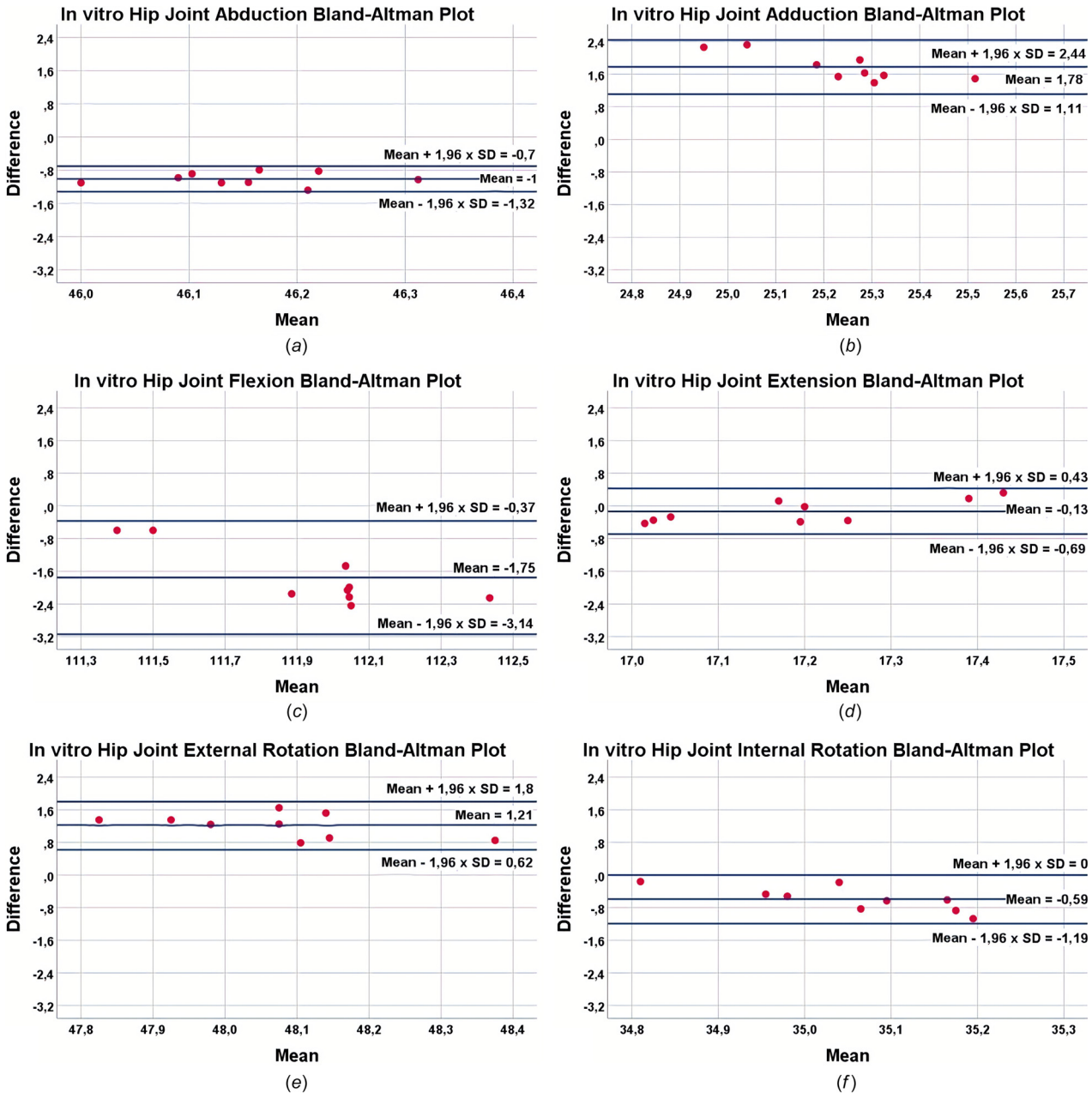

Fig. 7 Bland–Altman graphs based on the collected data from the in vitro setup for the hip, (*a*) abduction, (*b*) adduction, (*c*) flexion, (*d*) extension, (*e*) internal, and (*f*) external rotations using the dataset collected by SMARTSUIT PRO-and OptiTrack with three sets of three repetitions demonstrating the limits of agreement

In SMARTSUIT PRO, each sensor has a local coordinate system, each coordinate system has a designated place with fixed spaces between each sensor. By this means, the translation from the local coordinate system to global coordinate system was performed using rotational matrix calculations. For in vivo experiments, since each subject has different anthropometric measurement, the scale was adjusted accordingly before each measurement in the user interface of SMARTSUIT PRO. All the collected position and rotation data were transferred to the hub and used for rigid body motion model. SMARTSUIT PRO has the inherited soft tissue artifact problem of MOCAP systems, as it is the case with OptiTrack, which relies on the information collected from the surface markers [23]. Relating skin marker data to the bone marker data is another research topic and is not within the scope of this research. In literature, there are some other emerging medical devices such as biplanar radiography, which might eliminate the skin artifact problem and provide direct bone marker data. However, each system has its own pros and cons, as it is harder to get ethics permissions for healthy subjects due to use of ionizing radiations, and time-consuming data processing as well as limited field of view [24], which might be a problem for hip motion for our study. Yet, when compared with an optoelectronic MOCAP system [24], biplanar radiography RMSE showed angular errors ranging from 1.06 to 8.31 deg across the planes (frontal: 3.57 deg, 3.67 deg, transverse: 4.28 deg, 4.70 deg, sagittal: 2.45 deg, 2.67, walking and running, respectively), which are higher than the RMSE results of SMARTSUIT PRO, used in this study.

The collected data were used in the calculation of ROM values. The data collection rate was 100 frames per second for both of the systems, which made the comparisons and the postprocessing tasks convenient. If the data sampling rates were not equal, this would require matching of the sampling rate of the systems by utilizing up-sampling/down-sampling [25], signal-processing methods. While choosing an application, data collection rate is very

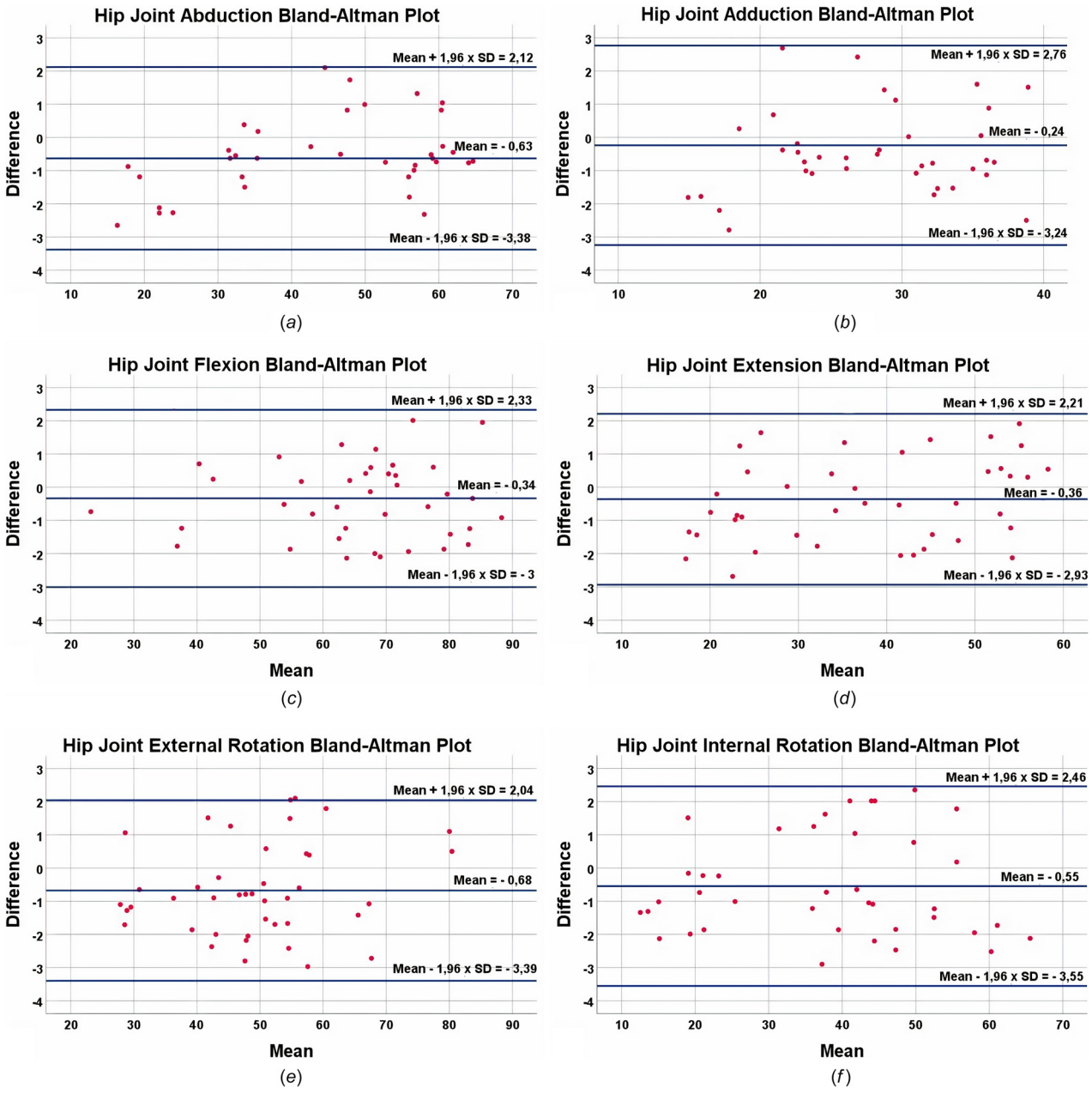

Fig. 8 Bland–Altman graphs based on the collected data from the volunteers for the in vivo part of the study for the hip, (*a*) abduction, (*b*) adduction, (*c*) flexion, (*d*) extension, (*e*) internal, and (*f*) external rotations using the dataset collected by SMARTSUIT PRO-and OptiTrack with three sets of three repetitions demonstrating the limits of agreement

important [26]. The researchers who are in need of designing a study and choose a MOCAP system should work toward optimum system design as too much data might be time-consuming to process and expansive to store, while inadequate sampling rate might cause missing on important details where peak accelerations take place. For example, for impact-related research, normally high-speed cameras are utilized with 1000 fps, in this case, use of SMARTSUIT PRO might not be the optimum solution. SMARTSUIT PRO has a fixed data sampling rate and this should be considered while designing experimental protocols in the field of biomechanics. It is the researcher's responsibility to choose the optimum measurement for the study which needs to investigated, it is advised a through literature analysis is conducted to choose an optimum equipment matching with the requirements of the investigation points.

In medical sciences, Bland–Altman graphs are widely utilized while introducing a new equipment into the field and comparing its performance to what is considered as gold standard in the field currently. Bland–Altman graphs provide detailed information for limits of agreements. These limits are calculated by using the mean and the standard deviation (s) of the differences between two measurements. The resulting Bland–Altman graph is a scatter plot in *XY* directions. The y-axis shows the difference between the two paired measurements (data from OptiTrack–data from SMARTSUIT PRO) and the *X*-axis represents the average of these measures ((Data from OptiTrack+ Data from SMARTSUIT PRO)/2), the difference of the two paired measurements is plotted against the mean of the two measurements. Normally during a measurement, we are not certain about the true value but we treat the gold standard system reading as a true value. If there is no difference between the readings, then y-axis value should be equal to zero, reporting perfect match between the readings and accuracy. The difference of this value from zero is known as bias [22]. If the tested system provides positive bias, it means that it underestimates the readings, negative means, when compared the gold standard, it overestimates the readings. In our results, for in vivo studies as indicated in Table 4, accuracy in other words bias of SMARTSUIT PRO is less than 1 deg. Only underestimating the extension motion by 0.4 deg, and overestimating the abduction/adduction, flexion, internal/external rotations maximum by 0.7 deg. This shows that SMARTSUIT PRO provides the required accuracy. The 95% of the data points in the scatter plot should lie within ±2 standard deviation of the mean difference. If all the data points fall into the limits of upper and lower boundaries, this is an indication of precision (more detailed graphical presentation of accuracy and precision graphs are available in Ref. [27]). In our dataset, results were within the upper and lower limits of agreement indicating precision of SMARTSUIT PRO data for this experimental protocol. Based on this experimental values, SMARTSUIT PRO can measure the ROM values of the hip joint as well as OptiTrack system.

In total, 14 people consisting of seven females and seven males were recruited in this study. To be able to calculate average ROM values, subjects were asked to repeat the motion three times, while their motion information was captured by the both systems. Although it could have been argued that for statistical analysis, it would be good to increase the number of subjects, due to limited amount of time and resources, the study was constrained in terms of population. The calculated RMSE between both systems was less than 1 deg in proof of concept part of the study. To comply with ISO13485 standards, we had set 2 deg of deviation for acceptance criteria before the experiments, results demonstrated that the system meets the required criteria. Based on this evidence, in vivo experiments were performed. Bland–Altman graphs were utilized to compare the data provided by both systems. Figures 7 and 8 show the agreement between the both systems indicating the 95% of the data falling into limits of agreement.

In the field of biomechanics, compatibility of MOCAP systems with the biomechanical simulation software is very important. We tested the compatibility of the data with BIOMECHANICS OF BODIES software (BoB Software) running on MATLAB environment, which was possible to calculate the angles and obtain ROM versus time graphs. There are also other open-source software such as OPENSIM; the suit is also compatible to work with this sort of platform, which might require more programming skills when compared to commercially available software. Based on the evidence provided in this technical communication, the next step is to design an experimental protocol for gait analysis providing detailed information for each phase of the gait cycle by making use of the biomechanical simulation programs mentioned.

In the materials section 2.1, it was mentioned that the SMARTSUIT PRO has a 6-h battery time. During our experiments, this was tested and the battery was able to survive for 6 h for us to complete our measurements. The ethics committee permission was obtained for healthy people. The experiment time for each subject was between 10 and 15 min. The subjects were able to wear the suit easily and reported no discomfort within the duration of the experiment. However, the suit has not been tested for patients. For example, with people who have disability, additional help might be required to wear the suit. The results reported in this paper are obtained from healthy volunteers. It is important to keep this in mind, while designing a study with specific patients, based on the results of this technical communication.

6 Conclusion

In medical engineering, when a device is utilized out of its intended use, it is mandatory to provide evidence that the device is fit for the new intended use. Here, we have investigated compatibility of the device for a simulation software, which is utilized for biomedical applications. We also cross validated the wearable MOCAP system against an optoelectronic system using Bland–Altman graphs. The evidence shows that the data provided by the wearable MOCAP system are comparable with the data of optoelectronic system. The new system has the advantage of not interfering with natural flow of daily life activities without the requirement of performing the data collection in a lab environment. However, as with any other surface-based MOCAP system, SMARTSUIT PRO-also suffers from the soft tissue artifact problem, but still has the advantage of ease of use with low data processing time to meet the limited time frames of busy clinical work flows. Being compatible with a biomechanical modeling software, this could be a game changer in future eliminating the need for high budgets, to conduct research worldwide.

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