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Validation method for body-mounted sensor attachments

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Abstract: Small sensor devices like inertial measurement units enable mobile movement and gait analysis, whereby existing systems differ in data acquisition, data processing, and gait parameter calculation. Concerning the validation, recent studies focus on the captured motion and the influence of sensor positioning with respect to the accuracy of the computed biomechanical parameters in comparison to a reference system. Although soft tissue artifact is a major source of error for skin-mounted sensors, there are no investigations regarding the relative movement between the body segment and sensor attachment itself. The aim of this study is to find an evaluation method and to determine parameters that allow the validation of various sensor attachment types and different sensor positionings. The analysis includes the comparison between an adhesive and strap attachment variant as well as the frontal and lateral sensor placement. To validate different attachments, an optical marker-based tracking system was used to measure the body segment and sensor position during movement. The distance between these two positions was calculated and analyzed to determine suitable validation parameters. Despite the exploratory research, the results suggest a feasible validation method to detect differences between the attachments, independent of the sensor type. To have representative and statistically validated results, further studies that involve more participants are necessary.

Keywords: body-mounted sensor; gait analysis; sensor attachment; sensor positioning; validation method.

Introduction

There are various motion tracking systems based on different technologies with continuously growing fields of

application. Especially for mobile measurements the skin-mounted sensors, such as small and low-cost inertial sensors, received attention in recent years. These sensors estimate the kinematic parameters like position and orientation of the segment, where the sensor is attached to. In existing studies inertial sensors have been validated with different reference systems by focusing on the comparison of the output data such as biomechanical parameters or event detection [1]. Besides, Forner-Cordero et al. proposed a method for the validation of body-mounted inertial sensor attachments by analyzing the influence of motion artifacts under various mounting conditions [2]. The accelerometer data was analyzed to describe the movement between body and sensor, and to find a model for compensating the soft tissue behavior in the output signal. The movement of the sensor attachment itself hasn't been considered.

The purpose of this work is to find a method to validate the various existing mounting and positioning options by determining parameters to describe the displacement between the body segment and the sensor. The validation method could be useful to evaluate attachments independently from the measuring module.

Materials and methods

Experimental protocol

Two different types of inertial sensor attachments were analyzed for the lower extremities (see Figure 1). Both designs were 3D printed with flexible material (TPU). The adhesive design was mounted with double coated medical tape (3 M 1522) directly on the skin. In total four adhesive attachments were fixed frontally and laterally on shank and thigh of one leg through all measurement series. The second attachment type is integrated into an elastic strap, which can be tightened around the human segment. Two sensors with this mounting option were attached to the shank and thigh of the other leg, whereby the orientation of the first test session is frontally and for the second laterally. To validate the attachments under real measurement conditions, each sensor was connected to a data logger, which was mounted by a strap with a fleece-velcro combination on the same segment.

The passive optical system Qualisys was used for motion tracking. The kinematic data was captured by 18 Oqus cameras with a sample rate of 200 Hz and eight Kistler force plates recorded the kinetic data with 1000 Hz. The passive markers were attached with double adhesive tape to the surface of all sensor fixings and directly to the skin, based on a biomechanical marker set (see Figure 2). For event detection a marker was placed at the calcaneus of each foot.

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Figure 1: Inertial measurement unit consisting of one data logger and sensor (A) with the strap (B) and adhesive attachment (C).

Figure 2: Subject set-up with the marker-set (16 body and six sensor markers), the strap (STR) and adhesive (ADH) attachments placed lateral (L) and anterior (A) on thigh (TH) and shank (SH).

Each series of measurements comprises five different movements, including walking, jogging, skipping, pounding and jumps from a 40 cm high platform into single-leg landings. As a consequence of the exploratory study both measuring series were performed by only one participant.

Data processing and analysis

First the raw kinematic and kinetic data was used for gait and movement event detection. Subsequently kinematic data was filtered by a zero-phase low pass Butterworth 4th order filter with a cut-off frequency of 10 Hz and pre-processed with Qualisys Track Manager 2019.3. The software facilitates to determine the 3D position of each segment by defining a 6DOF body of it. The necessary prerequisite for computing this rigid body (RB) is the positioning of at least three markers on each segment, which also have to be located in more than one plane. The origin of the local coordinate system of the RB is defined by calculating the average 3D position of the selected segment markers attached to the skin. The RB of the shank has been computed by the HF, TT, TIB and MT markers and of the thigh by the TH1, TH2 and FR markers. In addition to the 3D position of the origin of the segments, the residuals of the RBs and each single marker are included in data output.

For the ensuing data analysis Python 3.1.7 was used. The absolute distance between the 3D position of each RB origin and the 3D

Figure 3: Relative displacement between the sensor attachment marker and the certain segment for one gait cycle.

position of the marker, placed on each attachment on this certain segment, was computed over the whole measurement time. In the next step, the mean of the absolute distance was calculated, which represents the average distance between the segment body and the sensor marker. This offset has to be eliminated by subtracting the value from the absolute distance to get the relative displacement between the marker on the sensor attachment and the origin of the RB. Figure 3 shows exemplary this relative displacement normalized to the gait cycle for frontally positioning of the strap attachment on the shank and thigh.

Based on the analysis of the relative displacement, different validation parameters were defined. First, the averaged relative displacement was calculated for each gait cycle by dividing the sum of the absolute values by the number of samples per gait cycle. The second validation indicator is the maximum relative displacement.

Additional to this parameter, the cumulated residuals of the specific RB and the marker of the sensor mounting are shown in Figure 3. The residuals represent an accuracy evaluation of the tracked marker positions by the measurement system. Considering these cumulated residuals, the detectable displacement can be calculated, where the residuals pass through the zero line as in the example of the strap attachment mounted on the anterior thigh. Otherwise, the displacement is within the error limits of the measuring system as shown in the attachment on the shank. With the same calculation as for the relative displacement, the averaged and maximum detectable displacement were determined. In addition, the percentage of the samples with a detectable displacement over the whole gait cycle can be defined to make a statement whether the displacement occurs only for a short period of time and may therefore be caused by a specific event.

Results

The presented validation parameters are divided into the analysis of the relative and detectable displacement. The relative displacement indicates a dimension for the size of displacement, whereby the second parameter can be used to make a statement whether the captured displacement between sensor and segment can be detected by the applied measurement system at all.

Table 1 summarizes the results of the potential validation parameter of the different attachment conditions exemplary for walking. The results point out, that for all different positionings and types of the attachment mounted on the shank less than 1% of the analyzed samples of each gait cycle are within the range of the detectable displacement. The examination of the relative displacement of the attachments on this segment doesn't display any major differences between the positionings and types.

There is a considerable difference between the strap attachment placed anterior on the thigh (STR_TH_A) and the other attachments, especially regarding the detectable displacement, where on average nearly 50% of the residuals of each gait cycle do not include the zero line. In contrast the comparison of the maximum relative displacements shows less significant differences.

The analysis of the adhesive attachments on the thigh reveals in particular differences in the maximum values, whereby the maximum relative displacement of the anterior attachment is about half as high as the lateral one and therefore comparable to the detectable displacement.

Although five different activities were analyzed, in this paper the examination between various movements focusses representatively on the jogging and skipping data. The averaged relative displacement and percentage of samples with detectable displacement are shown in Figure 4.

Figure 4: Comparison of the averaged relative displacement and the percentage of samples with detectable displacement between jogging and skipping.

The validation parameters of the jogging data are comparable to the presented gait data, whereas the averaged relative displacement for nearly all attachments slightly increases for skipping compared to jogging, except the displacement of the STR_TH_A which decreases. Similar changes can also be seen in the percentage of the detectable displacements, where mainly only the adhesive attachments of the thigh show detectable displacement. Moreover, it is noticeable that the adhesive attachment of the lateral thigh varies greatly between the two movements.

Discussion and conclusion

This is the first study to investigate different body-mounted attachments and positionings independently from the sensor type. Parameters for the validation with an optical motion capture system were determined based on the analysis of the relative displacement between position of the RB and the corresponding sensor attachment for the lower extremities. Under consideration of the cumulated residuals of the single markers and RBs, measurable displacements between the attachment and segment can be identified. Therefore, an optical marker tracking system is a possible way to perform the validation. The relative and detectable displacements can be suitable parameters for the validation to analyze the range of the displacement and also provide an indication of the duration for the detectable displacement.

The analysis of the parameters in relation to the attachment positioning and type reveals slightly differences for the lower leg, whereas the deviations of the displacements between the attachments for the upper leg are even more pronounced. Thus, tendencies of the validation parameters can be observed under different attachment

Table 1: Analyzed validation parameters for walking with strap (STR) and adhesive (ADH) sensor attachments positioned lateral (lat.) and anterior (ant.) on thigh (TH) and shank (SH).

	n (steps)	Relative displacement		Detectable displacement		
		Avg. [mm]	Max. [mm]	Avg. [mm]	Max. [mm]	Pct. [%]
ADH	28	1.89	4.05	0.56	1.39	13.05
TH (ant.)		(0.10)	(0.42)	(0.21)	(0.69)	(3.89)
ADH	28	1.62	7.12	2.05	3.93	14.35
TH (lat.)		(0.18)	(1.01)	(0.42)	(0.93)	(4.27)
STR	10	4.25	7.81	1.82	4.18	48.97
TH (ant.)		(0.33)	(0.59)	(0.41)	(0.97)	(7.56)
STR	15	1.06	2.78	0.00	0.00	0.00
TH (lat.)		(0.13)	(0.28)	(0.00)	(0.00)	(0.00)
ADH	28	0.45	1.65	0.05	0.06	0.06
SH (ant.)		(0.07)	(0.57)	(0.28)	(0.33)	(0.33)
ADH	28	0.58	1.71	0.01	0.01	0.15
SH (lat.)		(0.06)	(0.15)	(0.02)	(0.03)	(0.37)
STR	10	0.57	1.69	0.03	0.05	0.58
SH (ant.)		(0.07)	(0.40)	(0.04)	(0.07)	(0.97)
STR	15	0.41	1.37	0.00	0.00	0.00
SH (lat.)		(0.05)	(0.11)	(0.00)	(0.00)	(0.00)

conditions. But the most relevant limitation to be considered, is the soft tissue artifact, which affects both the markers and sensor attachments. This displacement between the skin and the underlying bone can vary significantly between different subjects [3]. Therefore, it is necessary to increase the number of test persons in order to be able to make a statistically verified statement.

Due to the exploratory study design of this investigation, the number of analyzed steps is limited. Especially for the strap attachment, where the mounting orientation has been changed after the first measurement series from anterior to lateral due to limited space on the segments. This needs to be taken into account, particularly when comparing the positionings, because the computed displacements are not based on the same movement data basis. In addition, the displacement of strap attachments is influenced by the level of tightening, which can be a probable explanation for the described differences in the STR_TH_A. In contrast the positionings of the adhesive attachments remained unchanged over all measurements, which allows a statement about these different conditions.

Differences of the displacements between several types of movement can be determined for both segments. Consequently, by validating the attachments, it can be possible to select the type and positioning with the minimum displacement between segment and sensor for the performed movement.

The presented validation method depends on the accuracy of the applied measurement system and therefore, on the performed calibration procedure of the Qualisys system. Additionally, during the measurements the positions of all markers were not tracked at any time. The remaining gaps occurred especially in the kinematic jumping data for the time of landing. That indicates that the sample rate of 200 Hz has to be adjusted for further studies, to also avoid that described differences between movements are due to an insufficient sample rate.

However, this study shows that the validation of skin-mounted sensor attachments can be carried out with a

marker-based motion capture system and the presented parameters can be suitable to identify differences under various mounting conditions. By validating the attachments, the mounting positioning and type can be selected according to the field of application and the movement to be analyzed. This can consequently result in less displacement between sensor and segment and correspondingly to a more precise recording of the movement. Further research with a higher number of subjects is necessary to make reliable statements.

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