THE DEVELOPMENT OF AN IMU BASED MEASUREMENT SYSTEM FOR THE DETERMINATION OF THE SUBTALAR JOINT AXIS

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The subtalar joint axis influences biomechanical variables, especially regarding the lower limbs. The purpose of this study was to develop a measurement system for the subtalar joint axis based on inertial measurement units. Different development steps were taken, like an axis estimation algorithm using a principal component analysis and multiple approaches for the reference of the subtalar joint axis to the anatomical coordinate system. In the current development step, we try to solve the reference problem by using fused IMU data to track the offset to the foots longitudinal axis. As of now it is possible to determine the axis with a range of 4° for the inclination and 7° for the deviation within 5 measurements. Although, this approach leaves room for improvement, it could already be an acceptable method for large-scale studies and an easy-to-use alternative to imaging methods.

KEYWORDS: subtalar joint, IMU, inclination, deviation

INTRODUCTION: The movement of the subtalar joint can be described by a rotational axis (STA) which orientation is defined by its angle to the longitudinal axis of the foot in projection onto the transverse plane (deviation) and its angle to the transverse plane (inclination) (Alt, 2001). Literature gives no definite information regarding the range of the axis angles. In an overview from Piazza published in 2005 the deviation ranges from 1° to 47° and the inclination from 22° to 68° (Piazza, 2005). But as this orientation influences other biomechanical variables including the tibial rotation (Jones, 1945) and the muscle moment arms of the lower limbs (Zuppke et al., 2023), it has already been associated with various overload and injury mechanisms of the ankle, especially of the Achillis tendon (JONES, 1945; Reule et al., 2011; Tomaro et al., 1996). Established methods for the determination of an anatomical STA often rely on imaging procedures (e.g. CT, MRI), which not only entail increased stress for the subject but are also time-consuming and expensive and could therefore pose a hindrance to large scale studies. The calculation of a functional axis of the eversion and inversion movement might be a possible solution to those limitations. Inertial measurement units (IMU) play a major role in movement analysis for they are less expensive than other systems and provide more local flexibility. Therefore, they also can be a suitable choice for the analysis of the subtalar joint movement. The aim of this project is the development of a measurement system to determine a functional STA using IMU. We postulate for the subtalar joint to be a 1-degree-of-freedom system resembling a hinge with a rotation around a finite non helical axis. Based on the range reported by Piazza we decided on a target accuracy of $\pm$ 3° for both axis angles.

METHODS: There are multiple approaches to calculate joint rotation axes with IMU. The difficulty lies in the transmission of the axis orientation in the local sensor coordinate system (CS) to the global anatomical CS. For the definition of the anatomical CS of the foot, we follow the publication of Manter from 1941 (Manter, 1941).
STA measurement: The sole axis measurement procedure always stayed the same for all the following development steps: The subject is asked to sit down, place the shank on a stool in a way that they can move the foot freely and pull the foot in maximal dorsi flexion to lock the talocrural joint within the mortise. The examiner now applies the eversion-inversion movement to the foot while the gyroscope signal of one or two IMU gets recorded and processed using different algorithms. In the following descriptions of the different development steps (DS) this process is referred to as STA measurement.

DS 1 - The two-sensor solution with magnetic field calibration: Schlechtweg presents an STA algorithm for the calculation of deviation and inclination using two IMU and a kinetic model based on Seel et al. from 2012 (Schlechtweg, 2020). They explain a procedure to identify the rotational axis between two segments of a hinge using gyroscope data of one sensor on each segment (Seel et al., 2012). But the axis orientation refers to the local CS of the IMU. To solve this problem in this first DS the relative position of the IMU CS to the anatomical one is defined using the IMU magnetometer and a permanent magnet. The magnet generates a change in the magnetic flux density detected by the IMU, which dependents on the distance of the magnet to the sensor. Therefore, it is possible to measure the 3-dimensional distance between magnet and IMU. One IMU is attached to shank and one to the lateral hind foot in any orientation. The magnet is consecutively positioned at 2 different reference points on the arch of the foot along the longitudinal axis and 3 different reference points in the transverse plane while recording magnetometer data. The resulting signal is translated into distance data and the sensor position relative to the anatomical planes can be defined. After that follows the STA measurement. The tests for reliability and validity of the distance (measuring 14 cm in 10 repetitions resulted in $(14.45 \pm 0.01)\ cm$) and STA algorithm based on Seel et al. are described in the work from Schlechtweg and not part of this paper (Schlechtweg, 2020).

DS 2 - The one-sensor solution with magnetic field calibration: While the CS reference is still based on the magnetic field measurement, the STA algorithm was advanced in the second DS. By using a principal component analysis (PCA) on the gyroscope data of the hindfoot IMU, the direction of the eversion-inversion movement can be determined (figure 1b), without using any data from the shank IMU, making it redundant. The largest variation of the data, deciding the PCAs direction, should be between the passing of the neutral position of the foot out of the eversion movement and the passing of the neutral position out of the inversion movement. At these times the graph of the angular velocity should reach a maximum or a minimum.

DS 3 - The one-sensor solution with acceleration calibration: The magnet-based identification comes with a few limitations like the sensibility of the magnetic field against external disturbances (e.g. ferromagnetic materials) or a change of the properties of the magnet due to temperature effects, impacts, or other magnetic fields. For this reason, another calibration method for a CS reference was developed. The IMU is attached dorsal to the calcaneus using a hind foot adapter. A static acceleration measurement is conducted with the subject's foot flat on the ground using the IMU accelerometer to measure the IMU offset in pitch and yaw orientation relative to the transverse plane. For the roll orientation (the angle to the longitudinal axis of the foot) the foot is positioned in 90° on a wall for a second acceleration measurement (for the IMU setup: see figure 1c). The mean acceleration vectors resulting out of the two 5 second recordings can now be used to calculate the offset in roll, pitch, and yaw orientation. 8 STA measurements were done on one subject in order to test reproducibility. Sensor application and calibration was done again before each measurement. The median, interquartile range, and the range over all measurements is shown in table 1.

DS 4 - The one-sensor solution with quaternion calibration: The second acceleration measurement on the wall depends strongly on the positioning of the foot. Thus, the alignment of the IMU roll axis to the longitudinal axis of the foot still left room for improvement. The latest method includes a fusion of the gyroscope, accelerometer, and magnetometer data in the form of quaternions. The fusion is done automatically by the software of the used IMU model (aktos-mini, myon AG, Schwarzenberg, Schweiz). The IMU is positioned in line to the anatomical CS in some distance to the foot with help of a laser plummet. This sensor position is captured. The following attachment process of the sensor to the calcaneus is tracked as quaternion signal and the change in the roll orientation defined. The reproducibility test for this method was similar to the one described in DS 3. Three examiners conducted a set of 5 measurements on one subject and reattached the sensor after each run. The median, interquartile range, and the range over all measurements is shown in table 2.

Performance of the STA algorithm used from DS 2 onwards: The validity of the PCA algorithm was verified with a mechanical test rig simulating the movement of the subtalar joint for different predefined deviation and inclinations (figure 1a). The measurement settings included a range from 10° lateral to 40° medial deviation and an inclination range from 15° to

60°. The mean absolute error between the target values preset in the test rig and the actual measured values is the shown in table 3. To evaluate the repeatability of the STA measurement on a real foot, regardless of the IMU attachment and the CS, four examiners repeated the STA measurement (without reapplication of the sensor) 10 times on one subject. For the results see table 4.

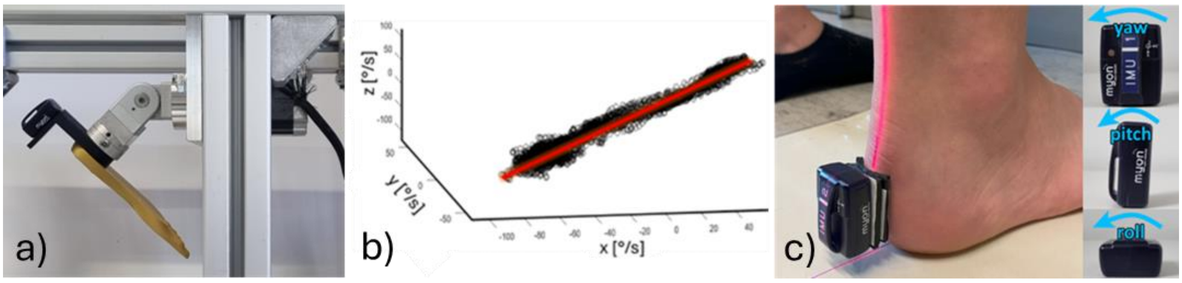

Figure 1: a) Test rig. b) Gyroscope data with PCA (red). C) IMU attachment to the hindfoot.

RESULTS:

DS 3:

Table 1: Results of the reproducibility tests on the subject using the procedure described in DS 3 (reapplication after each measurement).

	inclination	deviation
median [°]	41	12
interquartile range [°]	3	4
range (min / max) [°]	7 (38 / 45)	5 (9 / 14)

DS 4:

Table 2: Results of the reproducibility tests on the subject using the procedure described in DS 4 (reapplication after each measurement).

	inclination			deviation		
examiner	**1**	**2**	**3**	**1**	**2**	**3**
median [°]	41	47	43	9	10	10
interquartile range [°]	1	2	3	2	3	3
range (min / max) [°]	2 (40 / 42)	3 (45 / 48)	4 (41 / 45)	6 (7 / 13)	6 (6 / 12)	7 (6 / 13)

Performance of the STA algorithm used from DS 2 onwards:

Table 3: Results of the validity test on the test rig.

	inclination	deviation
mean absolute error [°]	0,4 ± 0,6	0,25 ± 0,4

Table 4: Results of the repeatability tests of the STA measurement (no reapplication between the measurements).

	inclination				deviation			
examiner	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
mean ± SD [°]	41 ± 1	47 ± 1	44 ± 1	46 ± 2	12 ± 2	10 ± 2	8 ± 1	12 ± 1
range (min / max) [°]	4 (40 / 44)	3 (45 / 48)	4 (42 / 46)	4 (44 / 48)	5 (9 / 14)	5 (7 / 12)	4 (6 / 10)	3 (10 / 13)

DISCUSSION: The test rig results showed that the PCA calculation method used to extract the axis of a hinge joint out of the gyroscope data seems to be valid and reliable, given the small mean absolute error and the small standard deviation for the inclination as well as for the deviation. In contrast the measurements on a human subject (table 4) resulted in higher standard deviations and also in differences between the four examiners. Although our target accuracy is still met, this indicates that the subtalar motion differs from the simple model of a hinge. The issue most difficult to solve is the reference of this axis to the anatomical CS of the foot. Although Schlechtwegs magnet calibration procedure allows a reliable construction of an anatomical CS in controlled settings, field trials showed that the magnetic field measurement poses a potential source of error. That is why we developed alternative approaches such as determining the sensor orientation by recording acceleration data or using fused IMU data (as described in DS 3 and 4). A comparison of tables 3 and 4 to table 1 shows that the accuracy is considerably influenced by the attachment of the IMU and the calibration process. That can likely be explained by different foot positioning during the calibration measurement. While the range for the inclination in table 3 is still too high, table 4 on the other hand shows acceptable results that are in accordance with the data of table 1. The inclination depends on the pitch and roll correction angles, which estimation is based on acceleration data in both, DS 3 and 4, using the same method. The measurements have to be repeated with more examiners and subjects to make a clear statement. The roll orientation, which influences the deviation, is the most critical factor as it strongly depends on the positioning of the foot on the wall. To avoid this, the latest DS 4 uses fused IMU data. But for now, this doesn't result in any enhancement. As this method also relies on the data processing, there is still a chance that we could succeed by developing it further.

CONCLUSION: In this paper we describe our DS for a simple, cost-effective IMU based STA measurement system. While we are positive about the validity of the STA estimation algorithm it could be worthwhile to considerate more complex models of the subtalar joint. Also, the referencing to the anatomical CS still leaves room for improvement. In future, we also will test, if a better hind foot adapter could help the examiner to attach the IMU directly in line with the foots longitudinal axis, making the identification of any offset in the yaw orientation unnecessary. However, for large-scale studies, the system's properties after development step 4 may already be sufficient to divide the subject collective into (e.g. 3) groups with low, middle, and high inclination and deviation angles to further examine the relationship between the orientation of the STA and other biomechanical parameters, as well as their role in the development of overuse injuries, without the need of imaging procedures. Of course, a higher differentiation should still be the next goal.

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