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A single Inertial Measurement Unit on the shank to assess the Shank-to-Vertical Angle

L.A.F. de Jong [a,b,*], Y.L. Kerkum [c], W. van Oorschot [a], N.L.W. Keijsers [a,b]

[a] Department of Research, Sint Maartenskliniek, Nijmegen, the Netherlands
[b] Department of Rehabilitation, Donders Institute for Brain, Cognition and Behaviour, Radboud University Medical Center, Nijmegen, the Netherlands
[c] Research and Development, OIM Orthopedie, Assen, the Netherlands

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ABSTRACT

The Shank-to-Vertical Angle (SVA) is a commonly used parameter to describe orthotic alignment. 3D gait analysis (3DGA) or 2D video analysis are usually used to assess the SVA, but are not always feasible in clinical practice. As an alternative, an Inertial Measurement Unit (IMU) attached and aligned to the shank might be used. This study aimed to investigate the validity, inter-rater reliability and optimal location of a single IMU on the shank to assess the SVA. Thirteen healthy participants (7 m/6f, mean age: 45 ± 18 years) were recorded during quiet standing and barefoot walking using a 3D motion capture system and, simultaneously, with IMUs on the shank. The IMUs were anatomically placed and aligned at two different locations, i.e. anterior, in line with the tibial tuberosity and midline of the ankle (anterior IMU), and lateral, in line with the lateral epicondyle and lateral malleolus (lateral IMU). For each participant, the IMUs were placed by two different researchers. A paired *t*-test, Bland Altmann analysis (mean difference, repeatability coefficient) and intraclass correlation coefficient (ICC) between the 3DGA and both IMUs, and between raters, was performed. Although validity and reliability of the lateral IMU was low, good validity and inter-rater reliability was found for the anterior IMU (Rater1: mean difference: −0.7 ± 2.1, p = 0.27; ICC = 0.83 and Rater2: mean difference: −0.4 ± 1.9, p = 0.46; ICC = 0.86). Hence, a single IMU placed at the anterior side of the shank is a valid and reliable method to assess the SVA during standing and walking in healthy adults.

1. Introduction

Ankle-Foot-Orthoses (AFOs), often in combination with orthopedic footwear (AFO-FC), are commonly prescribed to improve gait in patients with neurological disorders, such as spinal cord injury and stroke. The basic working mechanism of an AFO is to influence sagittal joint kinematics and kinetics by manipulating the ground reaction force (GRF) in relation to the joint rotation centers (Eddison and Chockalingam, 2013). AFOs have shown to normalize joint kinematics and kinetics (Brehm et al., 2008; Tyson et al., 2013), improve spatiotemporal parameters (Tyson and Kent, 2013; Wit et al., 2004) and, moreover, improve energy expenditure and gait capacity (Brehm et al., 2008; Danielsson and Sunnerhagen, 2004). However, the AFO effectiveness depends mainly on the alignment of the AFO, which should be individually optimized (Kerkum et al., 2015).

To optimize AFO alignment, fine adjustments are made to the AFO-FC, which is often referred to as tuning (Eddison and Chockalingam, 2013). These adjustments include adding heel wedges to incline the shank, and adjust footplate stiffness or footwear. In general, optimal AFO alignment is assumed when the GRF is as close as possible to the knee joint center during midstance, i.e. minimizing the knee flexion-extension moment (Jagadamma et al., 2009). A 3D gait analysis (3DGA) or 2D video analysis with force vector overlay can be used to assess the GRF in relation to the knee joint rotation center. However, these methods are restricted to a lab setting, expensive and time consuming (3DGA) and prone to errors (3DGA and 2D video), and therefore not always feasible in the outpatient clinic. As an alternative to the GRF in relation to the knee joint center, the Shank-to-Vertical Angle (SVA) at midstance is suggested as a parameter to evaluate AFO-FC tuning. The SVA, which is the angle between the anterior surface of the tibia and the vertical in the global sagittal plane (Owen, 2010), represents appropriate GRF alignment to the knee. Moreover, it

* Corresponding author at: Sint Maartenskliniek, department of Research, PO Box 9011, 6500 GM Nijmegen, the Netherlands.

E-mail addresses: l.dejong@maartenskliniek.nl (L.A.F. de Jong), Y.Kerkum@oim.nl (Y.L. Kerkum), w.vanoorschot@maartenskliniek.nl (W. van Oorschot), n.keijsers@maartenskliniek.nl (N.L.W. Keijsers).

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has been shown responsive to increasing the AFO-FC's heel height while wearing rigid AFOs (Eddison and Chockalingam, 2013; Jagadamma et al., 2010, 2009; Kerkum et al., 2015). It is assumed that a SVA at midstance between 7° and 15°, with an optimum of 10° to 12° indicates optimal GRF alignment to the knee (Owen, 2010).

As an alternative to 2D and 3D gait analysis, Inertial Measurement Units (IMUs) have been shown to adequately measure joint kinematics during walking and can be used to assess shank movement (Li et al., 2010; Mayagoitia et al., 2002; Seel et al., 2014). Moreover, IMUs can be used at relative low costs and outside a lab setting. For adequate measurements, a sensor-to-segment alignment, commonly determined with calibration postures or calibration movements, is advised. Considering that this is time consuming and has also its limitations, this would make it less applicable in clinical practice. Sensor-to-segment alignment might however be achieved by placing the IMUs in a way that the IMU's local coordinate system corresponds to the anatomical coordinate system, therewith avoiding the need of calibration. Yet, it is unknown whether this approach is accurate for assessing shank kinematics.

This study investigated the use of a single IMU on the shank to assess the SVA, without using standard sensor-to-segment calibration. The following three aims were studied: (1) to examine the validity of a single IMU on the shank to assess the SVA, (2) to examine the inter-rater reliability of a single IMU on the shank to assess the SVA, and (3) to determine the optimal location of the IMU on the shank to achieve IMU-to-shank alignment. It was hypothesized that a single IMU on the shank is a valid and reliable method, with ICCs above 0.8 and error values (standard deviations) lower than 2°, to assess the SVA.

2. Methods

2.1. Participants

Thirteen healthy adults (7 male, mean (SD) age: 45 (18) years) participated. Exclusion criteria were balance or gait problems, and leg or foot deformities. All participants signed written informed consent before the start of the study. Measurement procedures were in accordance with the Declaration of Helsinki. The study was approved by the regional medical ethics committee of Arnhem-Nijmegen (2018–4647) and by the internal review board of the Sint Maartenskliniek.

2.2. Equipment

Data were collected at the gait laboratory of the Sint Maartenskliniek. This laboratory consists of a 10 camera motion capture system (Vicon, Oxford, USA) and a force plate (Kistler Instruments, Hampshire, UK) embedded in the middle of a ten meter walkway. The motion capture system recorded marker data with 100 Hz, while the sample frequency of the force plate was 2400 Hz. Two IMUs (APDM, Portland, USA) were placed on the shank, which sampled at a frequency of 128 Hz. A trigger was implemented to synchronize the three systems.

2.3. Measurement procedure

Prior to the measurements, anthropometric data were collected. Subsequently, participants were instrumented with 20 markers according to the Plug-in Gait model and three additional markers on the shank by one researcher (LJ) (Fig. 1A). The IMUs were placed by two researchers at two locations on the shank: (1) anterior side in which the longitudinal axis of the IMU (Z_{ant}) was aligned with

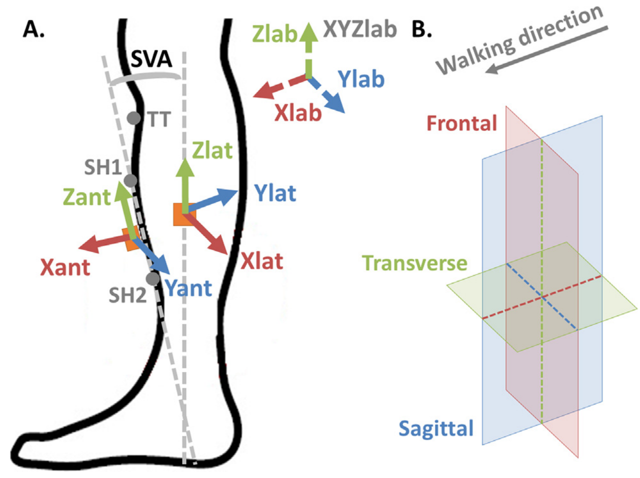

Fig. 1. A. Schematic overview of the lower leg with additional markers (grey dots), IMUs (orange rectangles), and the corresponding coordinate systems: XYZant for the anterior IMU, XYZlat for the lateral IMU, and XYZlab for coordinate system of the lab to express the shank markers. SVA: Shank-to-Vertical Angle, TT: Tibia tuberosity, SH1: shank marker 1, SH2: shank marker 2. B. Schematic overview of the frontal (red), sagittal (blue) and transverse (green) plane and the corresponding axes Xlab (red), Ylab (blue) and Zlab (green) of the lab. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the line connecting tibial tuberosity and midline of the ankle (anterior IMU), and (2) lateral side in which the longitudinal axis of the IMU (Z_{lat}) was aligned with the line connecting lateral epicondyle and lateral malleolus (lateral IMU) (Fig. 1A). The researchers placed the IMU by visual inspection in a way that the IMU was aligned with the shank in the frontal and transverse plane of the shank, which corresponds to the coordinate system of the lab (Fig. 1B). For each participant either the right or left leg was assessed, which was randomized across all participants.

Participants performed a standing and walking task. During the standing task, participants were asked to stand still with slightly bended knees for 5 s. During the walking task, participants walked barefoot at a comfortable speed along the 10 m walkway. When five correct trials were recorded (i.e. no irregular walking pattern observed, and a clean hit on the force plate of a single foot of the instrumented leg), the measurement was completed.

To assess the inter-rater reliability of the IMU placement, the IMUs were independently placed by two raters. The first rater (LJ) placed the IMUs and participants performed the tasks. Subsequently, the IMUs were removed while the markers remained on the participant's body. Afterwards, a second researcher (WO) placed the IMUs on the shank and the tasks were performed again. The order of the two researchers placing the IMUs was randomized across participants.

2.4. Data analysis

Marker data of the 3DGA was filtered with a zero lag, second order Butterworth filter with a cutoff frequency of 10 Hz and force plate data with a zero lag, second order Butterworth filter with a cutoff frequency of 7 Hz. Heel strikes and toe-offs were determined by the vertical component of the GRF. Heel strikes and toe offs were identified as the instant the vertical GRF respectively exceeded and dropped below the threshold of 25 N. Midstance was defined as 50% between heel strike and toe-off. The SVA measured with 3DGA (SVA_{3DGA}) was calculated as the angle in degrees between the anterior side of the shank, defined by the two markers at the anterior side of the shank (SH1 and SH2), and the vertical in the sagittal plane of the lab using the following equation:

$$SVA_{3DGA} = atan\left(\frac{posX_{SH1} - posX_{SH2}}{posZ_{SH1} - posZ_{SH2}}\right) * \frac{180}{\pi},$$

in which $posX_{SH1}$ and $posX_{SH2}$ are the position of the shank markers on the X-axis and $posZ_{SH1}$ and $posZ_{SH2}$ the position of the shank markers on the Z-axis of the global coordinate system of the lab (Fig. 1).

Acceleration, angular velocity and quaternion data of the IMU was used for data analysis of the IMU. Heel strike and toe-off were determined based on the angular velocity (Aminian et al., 2002). In the angular velocity signal, heel strike and toe-off were represented by two sharp negative peaks, whereas a large positive peak represented mid swing. Firstly, the large positive peaks were detected. Heel strikes and toe-offs were defined at the instants of the first and last negative peak after and before a large positive peak, respectively. These instants were used to determine midstance at 50% between heel strike and toe-off. Quaternions were transformed into rotation matrices, which were used to compute the SVA in degrees measured with the IMUs. The rotation of Z_{ant} around Y_{ant} for the anterior IMU and of Z_{lat} around X_{ant} for the lateral IMU were used to calculate the SVA. The following equations were used:

$$SVA_{IMUant} = 90 - atan\left(\frac{R_{IMUant_{1,3}}}{R_{IMUant_{3,3}}}\right) * \frac{180}{\pi}$$

$$SVA_{IMUlat} = 90 - atan\left(\frac{R_{IMUlat\_1,3}}{R_{IMUlat\_2,3}}\right) * \frac{180}{\pi},$$

in which R_{IMUant} and R_{IMUlat} are the rotation matrices of the anterior and lateral IMU, respectively.

A potential difference in SVA as measured by 3DGA or IMU, can be explained by the malalignment between the IMU axes and 3DGA axes and/or the difference in the timing of midstance. The angular difference between the IMU and 3DGA axes was calculated as the angle between Z_{ant} and the vector between the shank markers SH1 and SH2 in all three planes of the lab coordinate system (Fig. 1). The timing difference in midstance was calculated as the difference in midstance in milliseconds between the 3DGA and IMUS.

All data processing and analyses were performed using MATLAB 2018b (The MathWorks Inc, Natick, MA, USA).

2.5. Statistical analysis

Validity and inter-rater reliability were estimated using a paired *t*-test (α = 0.05), Bland Altmann analysis (mean difference, repeatability coefficient) and intraclass correlation coefficient (ICC) between the SVA_{3DGA} and both SVA_{IMUant} and SVA_{IMUlat} for each rater, and between the raters, respectively. The IMU location with the smallest standard deviation (SD) of the mean difference between the SVA_{3DGA} and SVA_{IMU} was considered as the optimal IMU-to-shank alignment. A paired *t*-test between midstance estimated with 3DGA and the IMUs was performed to reveal differences in the timing of midstance.

3. Results

3.1. Validity

The mean SVA_{3DGA} for standing was 15.6° (±5.7°) and 13.7° (±4.7°) for rater 1 and 2, respectively. The SVA_{3DGA} was significantly different from the SVA_{IMUant} for rater 1 (17.6° ± 5.1°, p = 0.003), and from the SVA_{IMUlat} for rater 1 (8.8° ± 4.7°, p < 0.001) and rater 2 (9.3° ± 4.7°, p < 0.001) (Table 1).

Table 1
Validity. Mean differences, repeatability coefficients, and intraclass correlations coefficients (ICCs) of the SVA between the 3DGA and both IMUs for both raters for standing and walking.

		Anterior IMU		Lateral IMU	
		Rater1	*Rater2*	*Rater1*	*Rater2*
Standing	Mean difference (SD)	−2.0° (1.9°)*	−0.9° (1.9°)	6.8° (3.5°)*	4.4° (3.4°)*
	Repeatability coefficient	3.7°	3.8°	6.9°	6.7°
	ICC	0.94	0.94	0.59	0.69
Walking	Mean difference (SD)	−0.7° (2.1°)	−0.4° (1.9°)	7.4° (2.8°)*	4.5° (3.2°)*
	Repeatability coefficient	4.2°	3.7°	5.6°	6.2°
	ICC	0.83	0.87	0.25	0.27

SD: standard deviation.
* Significant differences between the 3DGA and the IMU (p < 0.01).

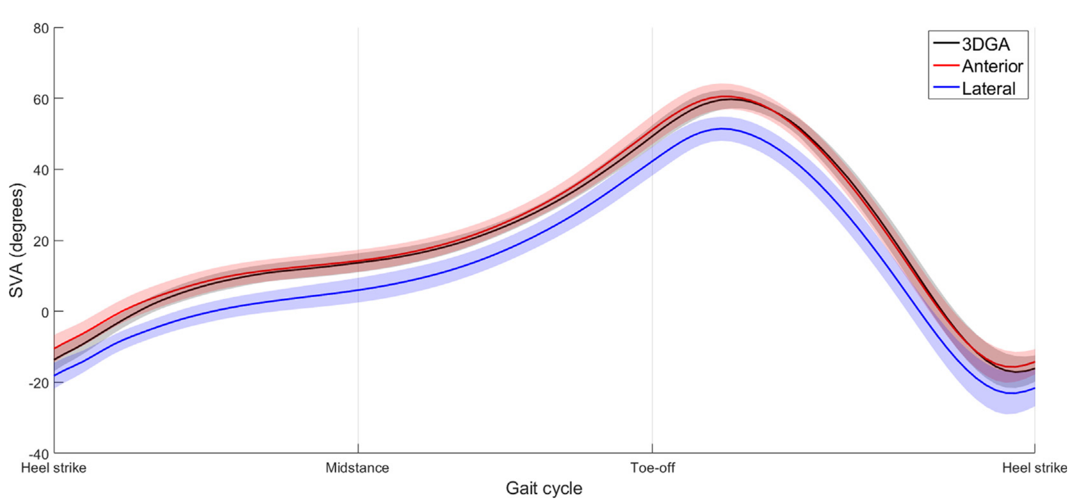

Fig. 2. Mean and standard deviation (shaded areas) of the Shank-to-Vertical Angle (SVA) during the gait cycle for 3DGA, the anterior IMU and the lateral IMU of Rater 1.

For walking, the mean SVA_{3DGA} was 13.7 (±2.7°) and 13.8 (±2.7°) for rater 1 and rater 2, respectively (Fig. 2). The SVA_{IMUant} at midstance was not significantly different from SVA_{3DGA} for rater 1 (14.4° ± 2.9°, $p = 0.26$) and rater 2 (14.1° ± 28°, $p = 0.52$) (Table 1 and Fig. 3). The SVA_{IMUlat} at midstance was significantly smaller compared to SVA_{3DGA} for rater 1 (6.3° ± 3.4°, $p < 0.001$) and rater 2 (9.3° ± 3.0°, $p < 0.001$) (Table 1 and Fig. 3).

3.2. Inter-rater reliability

No significant differences during standing between the raters were found for the SVA_{3DGA} ($p = 0.08$) and SVA_{IMUlat} ($p = 0.70$), whereas a significant difference was found for the SVA_{IMUant} ($p = 0.006$). During walking, no significant differences at midstance between the raters were found for the SVA_{3DGA} ($p = 0.78$) and the SVA_{IMUant} ($p = 0.67$). A significant difference in SVA_{IMUlat} at midstance between raters was found ($p = 0.003$) (Table 2).

3.3. Differences between the 3DGA and IMU

The angular difference between the 3DGA and IMU at midstance is presented in Table 3. The timing of midstance differed significantly between 3DGA and the anterior IMU with a 6.0 (±9.4, $p = 0.040$) and 6.6 (±9.8, $p = 0.031$) ms earlier midstance for the

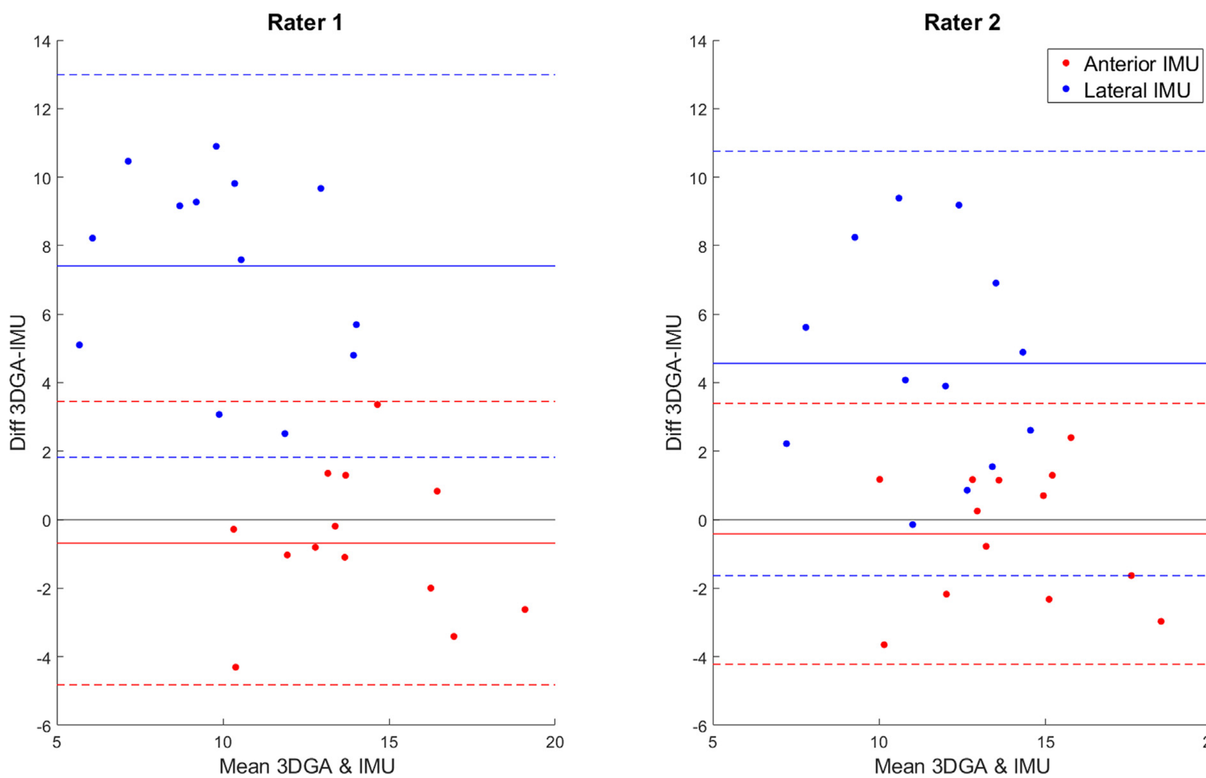

Fig. 3. Bland Altman plots of the SVA at midstance for both raters, showing mean difference (solid lines) and limits of agreement (dashed lines) for both IMUs.

Table 2
Inter-rater reliability. Mean differences, repeatability coefficients, and intraclass correlations coefficients (ICCs) of the SVA between the raters for 3D gait analysis (3DGA) and both IMU locations for standing and walking.

		3DGA	Anterior IMU	Lateral IMU
Standing	Mean difference (SD)	2.0° (3.8°)	3.1° (3.3°)*	−0.5° (4.4°)
	Repeatability coefficient	7.4°	6.5°	8.6°
	ICC	0.83	0.76	0.73
Walking	Mean difference (SD)	−0.07° (0.71°)	0.3° (2.4°)	−2.9° (2.8°)*
	Repeatability coefficient	1.4°	4.7°	5.7°
	ICC	0.98	0.79	0.62

SD: standard deviation.
* Significant differences between rater 1 and rater 2 ($p < 0.01$).

Table 3
Angular difference between the 3DGA and both IMUs for both raters for walking.

	Anterior IMU		Lateral IMU	
Plane	*Rater1*	*Rater2*	*Rater1*	*Rater2*
Frontal	1.2° (3.1°)	2.3 (3.6°)	−0.3° (3.1°)	2.4° (3.0°)
Sagittal	0.5° (2.1°)	0.1° (1.8°)	2.6° (2.7°)	2.3° (3.0°)
Transverse	−7.2° (13.0°)	−8.3° (11.7°)	−8.5° (14.9°)	−7.0° (10.7°)

Values are reported as mean (SD).

IMU for rater 1 and rater 2, respectively. For the lateral IMU, midstance was determined 9.0 (±9.6, $p = 0.006$) and 14.3 (±12.7, $p = 0.002$) ms earlier for rater 1 and rater 2, respectively.

4. Discussion

The present study investigated the validity, inter-rater reliability and optimal location for IMU-to-shank alignment to assess the SVA while standing and walking in healthy adults. The anterior IMU showed the best validity and reliability. The reported ICCs of above 0.80 for the anterior IMU indicated good validity, which were similar to the ICCs reported for 3DGA kinematics in the sagittal plane (ICC > 0.80) (McGinley et al., 2009). Likewise, the SDs of the difference with the 3DGA of 2° for the anterior IMU correspond to the reported and acceptable SDs for 3DGA sagittal plane kinematics (SD < 4°) (McGinley et al., 2009). Furthermore, the inter-rater reliability of the anterior IMU to assess the SVA was good and comparable to 3DGA with ICCs above 0.75 and SDs below 4° (McGinley et al., 2009). Hence, validity and inter-rater reliability was similar to 3DGA indicating that the anterior IMU is an adequate method to assess the SVA.

Our main outcome was the difference in SVA between the 3DGA and IMU. Since the markers were not removed, the difference in SVA_{3DGA} between the raters was a measure of consistency of the standing and walking task by the participants. We observed a small difference of 2° during standing and almost identical SVA_{3DGA} during walking. This indicates that they stood slightly different during the standing task, but walked similar after the raters placed the IMU. Therefore, the difference in SVA_{IMU} between the raters was related to differences in placement. The difference between SVA_{3DGA} and SVA_{IMUant} could be mainly caused by accuracy of the sensor fusion algorithms to assess the orientation, malalignment by placement and/or differences in assessing the timing of midstance. The main disturbances in orientation assessment by the IMU, linear acceleration and magnetic field distortion, seem to minimally affect the IMU due to slowing of the shank during midstance (Fig. 2) and sensor-to-segment alignment, respectively. Since the difference in midstance timing was only 6 ms, malalignment seems the main cause. Alignment was checked by calculating the angular difference between the longitudinal axis of the anterior IMU (Z_{ant}) and the vector between the shank markers. The mean angular difference of maximum 2.3° in the sagittal and frontal plane for the anterior IMU indicates adequate alignment with the shank. However, the large mean angular difference of around 8° and SD of around 12° in the transverse plane suggests difficulty to align the IMU in the transverse plane. Malalignment of the IMU could have introduced a shift of the IMU's reference frame, resulting in cross talk (i.e. not measuring the SVA in solely the sagittal plane). Moreover, it could introduce a more variable error between the methods and raters. This variable error, represented by the SD and repeatability coefficient, was clearly larger between 3DGA and the anterior IMU in comparison to the measurements with the 3DGA. To improve the accuracy of the IMU-to-shank alignment, the use of an alignment tool or addition of a calibration could be a solution to control the orientation of the IMU in the shank's anatomical coordinate system. The alignment tool will give a better indication of the orientation of the IMU relative to the shank, which could be used as a guidance to place the IMU. A simple calibration method of squats could be used to identify misalignment of the IMU.

In conclusion, a single IMU placed at the anterior side of the shank is a valid and reliable method to assess the SVA during standing and at midstance during walking in healthy adults. To be useful in clinical practice, the IMU needs to be valid, reliable and responsive to AFO tuning in patients walking with an AFO as well.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This study is part of the GaReC project, which is co-funded by OIM Orthopedie and the PPP Allowance made available by Health ~ Holland, Top Sector Life Sciences & Health, to stimulate public-private partnerships. Yvette Kerkum is employed by OIM Orthopedie. Neither OIM Orthopedie, nor Yvette Kerkum have (financial) benefits related to this project. There are no other conflicts of interest associated with this study.

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