INFLUENCE OF INERTIAL MEASUREMENT UNIT PLACEMENT ON KNEE FLEXION ANGLE MEASUREMENT DURING CYCLING

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Inertial measurement units (IMUs) enable measurements of joint kinematics during sports in the field. The purpose of this study was to investigate the use of IMUs for measuring the knee flexion angle during cycling. To expand the limited research on optimal placement of IMUs on body segments, three different IMU placement setups were tested. Joint angles were calculated from the IMU orientations via OpenSim. Kinematics were captured from six experienced cyclists and compared to optical motion capture. Apart from an amplitude offset between the angle courses measured by IMUs and optical motion capture, no significant differences were observed between measurement systems, regardless of the IMU placement setup. Thus, all IMU setups are comparable to optical motion capture in relative terms (RMSE between $3\ deg$ and $3.9\ deg$), but not in absolute values.

KEYWORDS: Kinematics, IMU, OpenSim, OpenSense, Optical Motion Capture.

INTRODUCTION: Cycling is a popular activity with numerous health benefits, such as improving fitness and reducing cardiovascular risk factors (Oja et al., 2011). Besides the benefits, excessive joint angles during cycling can increase the risk of injury (Bini et al., 2011), with the knee being a common site of injury (Silberman, 2013). Thus, measuring lower limb kinematics during cycling is of high interest. It is typically performed via optical motion capture, which is not feasible for outdoor measurements and limits studies to laboratory environments. Inertial measurement units (IMUs) offer more flexibility and are suitable for measurement of joint angles in the field (Al Borno et al., 2022). However, IMUs mounted on human body segments are susceptible to soft tissue artifacts (Cordillet et al., 2019), therefore, placement of the IMU sensors might be crucial. There has been limited work on optimizing the placement of IMUs on body segments to reduce soft tissue artifacts (Niswander et al., 2020), and to the best of the authors' knowledge, no study investigated different IMU placements for cycling. The aim of this study was to identify guidelines for practical application of IMUs for measuring cycling kinematics in the field. We investigated the effect of IMU placement on the measurement accuracy of the knee flexion angle during cycling. Due to the individual calibration procedures, it was hypothesized that knee flexion angles derived from IMUs do not differ from measurements with optical motion capture, regardless of the IMU placement.

METHODS: Six male experienced cyclists (age: $26 \pm 1.4\ yrs$; height: $185.5 \pm 2.6\ cm$; body mass: $79 \pm 6.6\ kg$) gave their informed consent and participated in the study. Each subject cycled more than $2000\ km$ in the year 2022, was able to sustain a power per bodyweight of $2\ Wkg^{-1}$ for $30\ min$ and had no acute lower limb injuries in the six months prior to participation. For the study, the subjects cycled on a road bike (FR5, Felt Bicycles LLC, Irvine, CA, USA), which was mounted on a stationary resistance trainer (Neo Smart, Tacx B.V., Wassenaar, Netherlands). According to the LeMond method, the saddle height was set to $88{,}3\%$ of the subject's inseam length (Bini et al., 2011). Additionally, the bike was equipped with power pedals (Assioma Duo, Favero Electronics Srl, Arcade, ITA) and a bike computer (Edge 530, Garmin Ltd., Olathe, KS, USA) to monitor cadence and power.
After a ten-minute warm-up, the subjects performed three one-minute cycling trials at a cadence of $80 \pm 5\ RPM$ and at a power of $2\ Wkg^{-1}$, with a one-minute break in between. During the trials, kinematics of the right leg were captured using four 60 Hz IMUs (Xsens DOT, Xsens Technologies B.V., Enschede, NLD) and an optical motion capture system with ten

Vicon Bonita cameras (Vicon Motion System Ltd., Oxford, GBR) recording at 100 Hz. Three IMU placement setups were considered in this study, which differed in the placement of the thigh and shank IMUs (Figure 1). The *lateral* setup was used for cycling in a previous study (Neumeister, 2020), the *anterior* setup showed accurate results for knee flexion (Niswander et al., 2020) and the *xsens* setup is recommended by the manufacturer of the IMUs (Xsens Knowledge base, 2023). In a randomized order, every subject performed one cycling trial with each IMU setup.

(a) lateral (b) anterior (c) xsens

Figure 1: Illustration of the IMU placements on the body segments.

For calculating knee flexion angles from the IMU orientations, inverse kinematics was performed with the biomechanical simulation software OpenSim (version 4.4; Delp et al., 2007; Seth et al., 2018) and the Rajagopal model (Rajagopal et al., 2016). More specifically, the OpenSense workflow was used, since it is compatible with IMU orientation data (Al Borno et al., 2022). Before each trial, the IMUs were placed according to one of the IMU setups and their orientation relative to the body segments was calibrated by capturing one second of data with the subjects standing upright in a neutral position. From that, OpenSense calculated fixed rotational offsets. In addition, a magnetic field mapping was performed on the IMUs to account for environmental magnetic disturbances. Passive reflective markers were placed on the subjects according to the Plug-in Gait lower body marker set (Kadaba et al., 1990) and knee flexion angles during the trials were recorded and calculated with Vicon Nexus 2.12.

The knee flexion angles from both measurement methods were synchronized at the change from stationary to pedaling at the beginning of each trial. The first $35\ s$ were cut off, since the subjects had to reach the specified power and cadence. Subsequently, the angles were segmented into crank cycles, using the respective knee angle maxima for separation. The cycles were linearly interpolated to 360 timesteps and averaged over all cycles for each trial and subject. As metrics, the minimum (MIN), maximum (MAX) and range of motion (ROM) were determined for the averaged cycles. Furthermore, the root mean square error (RMSE) and correlation coefficient (CC) were computed between the angles obtained with IMUs and optical motion capture. To assess the influence of constant offsets, the angles from IMU measurements were shifted, so that the angle of the first timestep equals the angle from optical motion capture (offset adjustment). All data processing was performed in Matlab (R2021a, The MathWorks, Inc., Natick, MA, USA) and one trial was excluded due to erroneous IMU orientations.

For statistical analysis R (R Core Team, 2020) was used. Normality and homogeneity of variance were tested using a Shapiro-Wilk and Levene's test, respectively. Differences in MIN, MAX and ROM between the IMU and optical motion capture angles were examined over all subjects using a paired Student's t-test. To investigate differences in RMSE and CC between the three IMU setups, a repeated-measures analysis of variance (ANOVA) was performed. The significance threshold for all tests was $p < 0.05$.

RESULTS: Figure 2a shows that the angles measured by IMUs and optical motion capture follow a similar progression throughout the crank cycle. An amplitude offset is present, which is least pronounced for the *anterior* setup. The difference in MIN and MAX between the optical and IMU angles is significant for the *lateral* and *xsens* setup (Table 1). The RMSE is lowest for *anterior* (Table 2). In the offset adjusted angles (Figure 2b) a significant difference is only observed for MAX in the *lateral* setup (Table 1). The RMSE is lower with offset adjustment than without (Table 2). Lastly, CC shows strong positive correlation in all conditions and no significant differences were found between the IMU setups for RMSE and CC (Table 2).

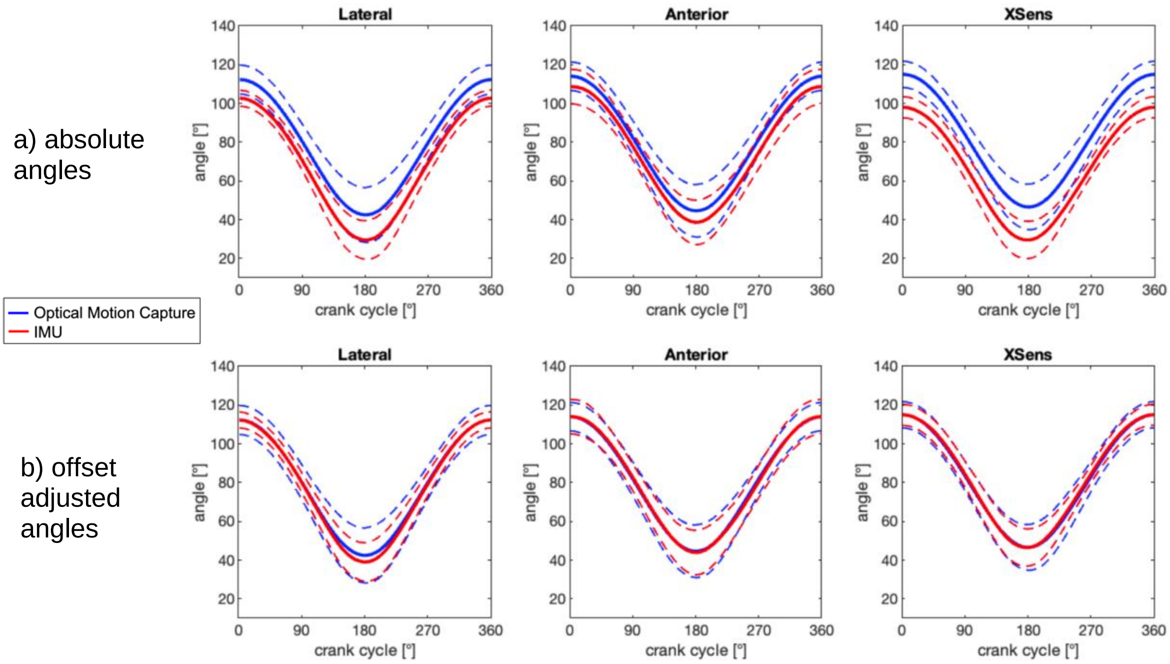

Figure 2: Mean (± SD) knee flexion angle of all subjects measured with IMUs and optical motion capture, ordered by IMU placement. a) shows the absolute and b) the offset adjusted angles.

Table 1: Mean (± SD) across all subjects of MIN, MAX and ROM of the knee flexion angle measured with IMUs and optical motion capture. The p-value is bold if below 0.05.

		Absolute			Offset Adjusted		
		lateral	anterior	xsens	lateral	anterior	xsens
MIN [deg]	Optical	42.4 ± 14.2	44.6 ± 13.6	46.6 ± 11.8	42.4 ± 14.2	44.6 ± 13.6	46.6 ± 11.8
	IMU	29.4 ± 10	38.6 ± 11.5	29.5 ± 9.7	39 ± 15.9	44 ± 18.2	46.5 ± 17.8
	p-value	**0.014**	0.159	**0.004**	0.255	0.804	0.974
MAX [deg]	Optical	112.3 ± 7.5	114.1 ± 7.3	115.1 ± 6.8	112.3 ± 7.5	114.1 ± 7.3	115.1 ± 6.8
	IMU	102.8 ± 4.2	108.7 ± 8.9	98.1 ± 5.4	112.4 ± 7.5	114.1 ± 7.3	115.1 ± 6.8
	p-value	**0.022**	0.276	**0.022**	**0.003**	0.372	0.235
ROM [deg]	Optical	69.9 ± 8.7	69.4 ± 8.9	68.5 ± 7.4	69.9 ± 8.7	69.4 ± 8.9	68.5 ± 7.4
	IMU	73.4 ± 8.8	70.1 ± 12.4	68.6 ± 11.9	73.4 ± 8.8	70.1 ± 12.4	68.6 ± 11.9
	p-value	0.252	0.805	0.971	0.252	0.805	0.971

Table 2: Mean (± SD) across all subjects of RMSE and CC between the knee flexion angles measured with IMUs and optical motion capture. The p-value is bold if below 0.05.

		lateral	anterior	xsens	p-value
Absolute	RMSE [deg]	12.4 ± 5	8.7 ± 5.4	16.7 ± 7.4	0.108
	CC	0.998 ± 0.002	0.999 ± 0.001	0.999 ± 0.001	0.338
Offset Adjusted	RMSE [deg]	3.3 ± 1.3	3 ± 1.4	3.9 ± 1.8	0.616
	CC	0.998 ± 0.002	0.999 ± 0.001	0.999 ± 0.001	0.338

DISCUSSION: Without offset adjustment, the *anterior* setup is preferable due to its lower amplitude offset. However, the *anterior* setup was not significantly different from the other two setups in terms of RMSE, despite showing the lowest value. A larger sample might lead to more conclusive results. The offset adjustment mitigated the amplitude offset for all IMU setups which in combination with the high CC shows that the observed offset in the IMU measurements is constant throughout the crank cycle. A reason for the amplitude offset could be that the IMU angles were calibrated with the subjects standing in a neutral upright position,

which could have offset the angles depending on the exact pose of the subjects. Compared to *anterior, lateral* and *xsens* show higher amplitude offsets and have in common that the thigh IMU was placed lateral, indicating that thigh IMU placement impacts the vertical offset. For MAX with the *lateral* setup, the significant difference between the optical and offset adjusted IMU angles could stem from crank cycle separation at the knee angle maxima. Matlab included end indices in the separation interval, so that the first and last timesteps of each crank cycle were maxima. For all IMU setups, the RMSE decreased considerably through offset adjustment, so that the RMSE values fall within the range of previous studies (Cordillet et al., 2019; Niswander et al., 2020; Al Borno et al., 2022).
Overall, no ROM differences between the IMU and optical angles were found, as well as no CC differences between the IMU setups. Moreover, the offset adjustment did not change the ROM and CC. The study showed that, for cycling, all three IMU placement setups may be used in combination with OpenSense to overcome the limitations of optical motion capture and to enable the measurement of knee flexion angles in the field. However, the results suggest that the IMU derived kinematics can be compared to other measurement systems only in relative terms, not in absolute values, since the calibration might lead to amplitude offset.

CONCLUSION: In summary, this study combined three IMU placement setups with inverse kinematics to measure knee flexion angles during cycling. Kinematics measured with all three IMU setups were comparable to optical motion capture if amplitude offset is disregarded. In contrast to optical motion capture, the presented IMU approach offers an accessible way to analyze cycling kinematics in the field, helping to reduce the risk of injury and to optimize performance. To further support practical application, studies should investigate the measurement of joint angles with three degrees of freedom. Moreover, longer duration cycling trials should be investigated to assess the influence of IMU drift.

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