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Trunk inclination estimate during the sprint start using an inertial measurement unit: a validation study

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Abstract

The proper execution of the sprint start is crucial in determining the performance during a sprint race. In this respect, when moving from the crouch to the upright position, trunk kinematics is a key element. The purpose of this study was to validate the use of a trunk-mounted Inertial Measurement Unit (IMU) in estimating the trunk inclination and angular velocity in the sagittal plane during the sprint start. In-lab sprint starts were performed by five sprinters. The local acceleration and angular velocity components provided by the IMU were processed using an adaptive Kalman filter. The accuracy of the IMU inclination estimate and its consistency with trunk inclination were assessed using reference stereophotogrammetric measurements. A Bland–Altman analysis, carried out using parameters (minimum, maximum, and mean values) extracted from the time histories of the estimated variables, and curve similarity analysis (correlation coefficient > 0.99, Root Mean Square Difference < 7 deg) indicated the agreement between reference and IMU estimates, opening a promising scenario for an accurate in-field use of IMUs for sprint start performance assessment.

Keywords: biomechanics, sport, motion analysis, Kalman filter, Micro-Electrical-Mechanical Systems

Introduction

An effective start is crucial for successful sprint running performance and directly affects 60 to 400 m sprint times.[1,2] To date, research on sprint start performance has mainly focused on the lower part of the body. In particular, a medium antero-posterior spacing between the feet on the blocks,[1,3] short reaction times,[1,4,5] and large forces, powers and impulses exerted on the blocks[6-8] were shown to benefit 10 and 20 m sprint times.

While the importance of the trunk movement during the sprint start has been acknowledged by expert coaches,[9] only a few studies have focused on the upper part of the body.[7,10-13] In particular, trunk inclination during the “set” position was found to correlate with times at 10 and 20 m,[11] while during the block start phase, from the “on your marks” to block clearing,[9] trunk angular velocity was reported to discriminate between high and medium level sprinters.[13] None of these studies, however, monitored the trunk during the pick-up phase, i.e. the phase ranging from block clearing to the upright position.[9]

Such monitoring is allowed in-the-field by wearable Inertial Measurement Units (IMUs), embedding a three axes accelerometer and gyroscope. So far, IMUs have been used for sprint running analysis to estimate foot-ground contact times[14,15] and lower leg rotational kinematics,[16] while trunk motion was assessed with IMUs only during daily-life activities or under slow flexion-extension, lateral bending and torsion.[17,18] The methodology used in these studies, however, cannot be extended to the sprint start for two reasons. First, the movements of the soft tissues separating the IMU from the skeleton,[19] to be considered as an artifact, are larger during sprint running compared to daily-life activities, to the extent that they may jeopardize the outcome.[20] Second, the accuracy of the IMU orientation estimate, based on sensor-fusion algorithms, depends on the relative importance given to the acceleration, which is more reliable during quasi-static phases, and to the angular velocity, prevailing during jerked phases.[21] This relative importance reverses when dealing with the sprint start as opposed to daily motor acts, requiring sensor-fusion algorithms to be specifically adapted and tested.

Within this framework and to supplement track and field coaches, the purpose of this study was to validate the use of a trunk-mounted IMU in estimating the trunk inclination and angular velocity during the sprint start. To this aim, an adapted sensor-fusion algorithm was tested and the reliability of the IMU estimates was assessed by comparison with stereophotogrammetric data.

Methods

Experimental set up and data acquisition

Five male sprinters (age: 23.8±0.8 y; mass: 72.4±3.8 kg; stature: 1.79±0.07 m) gave their informed consent to participate in the study, which received ethical approval. The athletes were currently competing over 100 or 200 m and their best times for 100 m ranged from 11.21 to 11.50 s. Each sprinter, wearing his running shoes without spikes, was asked to perform four sprint starts from the starting-blocks, individually set and embedded in the floor of an indoor laboratory (12 m length). The block start phase and the first three steps of each start were analyzed.

The athletes were equipped with an IMU (FreeSense, Sensorize Ltd, Italy) containing a 3D accelerometer and a 3D gyroscope (± 6 g and±500 deg·s^{-1} of full range, respectively; 100 samples·s^{-1}) providing linear acceleration and angular velocity components, respectively along and about the axes of a unit-embedded frame (IMU local reference frame: $\mathbf{L}_{IMU}$). The IMU was mounted so that its axes were parallel to the trunk anatomical axes (Figure 1). The unit data were transmitted via Bluetooth® to a laptop computer. Careful attention was paid to the fixation of the IMU on the lower back trunk (L2 level) to limit its oscillations relative to the skeleton.[19] To this aim, an *ad-hoc* elastic belt was used along with a memory foam material placed between the paravertebral muscles and the IMU.

To validate the IMU estimates, a nine-camera stereophotogrammetric system (Vicon MX3, Oxford, UK, 200 samples·s^{-1}) was used. Four retro-reflective markers were attached to the IMU and five on the subjects' trunk (Figure 1) to determine the orientation of the unit and of the trunk, which was considered to be rigid and described as a line joining shoulder and hip joint centers.[9] A synchronization task (sudden trunk flexion-extension from standing) was performed at the beginning of each trial.

Data analysis

To remove random noise, marker and IMU data were low-pass filtered using a 40-points moving average filter (*smooth* function, *loess* method, Matlab®, MathWorks, MA). A global inertial reference frame ($\mathbf{G}_{IMU}$) was defined in a static phase aligning the x-axis of $\mathbf{L}_{IMU}$ with the gravity vector (Figure 2). The orientation matrix of $\mathbf{L}_{IMU}$ with respect to $\mathbf{G}_{IMU}$ was computed through an adaptive Kalman filter,[22] *ad hoc* designed to combine the information provided by the accelerometer and the gyroscope during the static and non-static phases of the analyzed motor task. The ratio between two noise sources associated to the two sensors ($r_{gyro/acc}$) was adaptively modified during the sprint start to suit the characteristics of the movement. In particular, a threshold (t) was defined for the difference between predicted and measured values of the system state,[22] i.e. the IMU inclination in the sagittal plane. Below t, $r_{gyro/acc}$ was set to use the accelerometer and the IMU inclination was computed through a quaternion based approach;[23] above t, $r_{gyro/acc}$ increased in favour of the gyroscope, and the unit inclination was estimated by integrating the angular velocity around the y-axis, with the initial conditions obtained by the accelerometer-based estimates. *Ad hoc* trials were performed to select the following initial values of the Kalman filter parameters:[24] t = 0.5 deg, and $r_{gyro/acc}$ equal to 1 and 100 deg·s·m^{-1}, below and above the threshold t, respectively.

To obtain reference values, a stereophotogrammetric local reference frame ($\mathbf{L}_S$) was defined (Figure 2) and its orientation in the stereophotogrammetric global reference frame ($\mathbf{G}_S$) was obtained in each instant of time. In order to compare the orientation of $\mathbf{L}_S$ and $\mathbf{L}_{IMU}$ in the same global reference frame, the latter had to be expressed with respect to $\mathbf{G}_S$. To this aim, the time-invariant rotation matrix relating the stereophotogrammetric and the IMU global reference frames was calculated, assuming that $\mathbf{L}_S$ was coincident with $\mathbf{L}_{IMU}$ at time zero (Figure 2). To compare the IMU orientation with the whole trunk orientation, a trunk anatomical frame ($\mathbf{A}_{TR}$) was defined (Figure 1) and its orientation with respect to $\mathbf{G}_S$ obtained in each instant of time. Finally, Tait–Bryant angles (axis mobile rotation sequence: yxz) were calculated with respect to $\mathbf{G}_S$, from the orientation of $\mathbf{L}_{IMU}$, $\mathbf{L}_S$ and of the whole trunk $\mathbf{A}_{TR}$. The rotation about the y-axis, referred to as angular displacement β, was further considered.

Four phases were identified using β: on your marks (OYM), transition (TNS), set (SET), and pick-up (PCK) (Figure 3). The average β values during OYM and SET (β_{OYM} and β_{SET}), the variation from β_{OYM} to β_{SET} ($\Delta\beta$), and the peak angular velocities during TNS and PCK (ω_{TNS} and ω_{PCK}) were computed from each curve. The absolute difference between each parameter set, as obtained from $\mathbf{L}_{IMU}$ and $\mathbf{L}_S$ (IMU accuracy), and from $\mathbf{L}_{IMU}$ and $\mathbf{A}_{TR}$ (IMU-trunk consistency), was then evaluated ($\mathbf{\Delta}_{IMU}$ and $\mathbf{\Delta}_{TR}$).

Statistical analysis

To assess both IMU accuracy and IMU-trunk consistency, the β curve as obtained from $\mathbf{L}_{IMU}$ was compared to those obtained from $\mathbf{L}_S$ and $\mathbf{A}_{TR}$, respectively. To this aim, the difference between β_{OYM} obtained from the $\mathbf{L}_{IMU}$ and $\mathbf{A}_{TR}$ was computed (β_{OFF} = 18±4 deg) and proved to be consistent within subjects (P = .675). Thus, β_{OFF} was removed from the trunk curves, and the Pearson’s correlation coefficient (r) and the Root Mean Square Difference (RMSD) were computed to assess the curve similarity. RMSD was also expressed in percentage of $\Delta\beta$ ($RMSD_{\%}$). The same coefficients were assessed for the PCK phase alone (r_{PCK}, $RMSD_{PCK}$, $RMSD_{\%PCK}$), which is the most affected by inertial factors. After a normal distribution test (Shapiro-Wilk test), the effect of the factor athlete was verified on all parameters and absolute differences by a repeated-measures one-way ANOVA, and descriptive statistics (mean±Standard Deviation (SD)) was performed (SPSS Inc. 17.0, Chicago, IL, USA; alpha = 0.05). Moreover, to assess the agreement between IMU and stereophotogrammetry, Bland–Altman analysis of $\mathbf{\Delta}_{IMU}$ and $\mathbf{\Delta}_{TR}$ was performed,[25,26] and the absence of heteroscedasticity[27] was verified.

Results

For the IMU accuracy, β curves from $\mathbf{L}_{IMU}$ and $\mathbf{L}_{S}$ presented a $RMSD_{\%}$ lower than 4±3 % and a high correlation (r) during the whole trial and the PCK phase alone (Table 1). After removing β_{OFF}, which was found to be different among athletes ($P = .001$), similar results were obtained for the IMU-trunk consistency (Table 1).

All parameters and absolute differences proved to be normally distributed. While all estimated parameters differed among athletes ($P < .001$), no statistical differences resulted for $\mathbf{\Delta}_{IMU}$ and $\mathbf{\Delta}_{TR}$ ($P > .15$). $\mathbf{\Delta}_{IMU}$ and $\mathbf{\Delta}_{TR}$ for the angular displacement parameters (β_{OYM}, β_{SET}, $\Delta\beta$) were lower than 1 deg and 4 deg, respectively, while Estimated values of $\mathbf{\Delta}_{IMU}$ and $\mathbf{\Delta}_{TR}$ for ω_{PCK} were found to be lower than 9 and 6 deg·s^{-1}, and decreased to 8 and 4 deg·s^{-1} for ω_{TNS} (Table 2). Bland–Altman plots indicated a good agreement for both IMU accuracy and IMU-trunk consistency. Symmetry of the confidence interval of $\mathbf{\Delta}_{IMU}$ and $\mathbf{\Delta}_{TR}$ was observed for all estimated parameters, indicating that no systematic error was present. Moreover, no heteroscedasticity was found for all parameters included in $\mathbf{\Delta}_{IMU}$ and $\mathbf{\Delta}_{TR}$ (overall average correlation = 0.09±0.41).

Discussion

The reliability of a lower-trunk mounted IMU in estimating the trunk inclination and angular velocity during the sprint start was assessed. Although in the present study, athletes were forced to complete the task in a relatively short distance, the average peak angular velocity of the trunk ($\mathbf{A}_{TR}$: $\omega_{PICK\text{-}UP}$ = 198±31 deg·s^{-1}) was comparable with previous literature results[7,13] (170±60 deg·s^{-1} and 186±48 deg·s^{-1}).

The accuracy of the estimate of the IMU rotation about one of its local axes was supported by the agreement between the unit and the reference estimates. Such agreement proves that the main limitations concerning the use of IMUs[19,20] do not have a detrimental effect on the unit inclination estimate, even during the most jerked phase of the sprint start. In particular, the efficacy of the implemented adaptive Kalman filter is attested by the strong curve similarity,[28] which also suggests that the site and method of the unit attachment were effective in limiting the effects of the soft tissue movements.

The IMU and trunk inclinations were in agreement during the whole trial and during the PCK phase alone. However, they presented an initial offset, β_{OFF}, which had a negligible variability over repeated measurements, but was subject-dependent. This offset (18±4 deg) depends on the trunk model commonly used by coaches and adopted in the study, i.e. rigid trunk. After β_{OFF} removal, $\mathbf{\Delta}_{TR}$ increased moving from the OYM (0±1 deg) to the SET phase (4±4 deg), indicating a change in the athletes’ kyphosis and neck extension and further supporting the inadequateness of a rigid trunk model. On the one hand, these results suggest the importance of trunk movement in determining the sprint start performance given the key role of the spine muscles during explosive motor tasks,[29] in terms of strength as well as of control. On the other hand, a comparison between the IMU orientation and the lower trunk, where the unit was located, would reasonably reduce, or even reset $\beta_{OFF,}$ and would be independent from changes in the upper spine. Indeed, strong correlations (r) obtained for all athletes and trials suggest that tracking only the lower trunk should not prevent describing the overall start strategy. Moreover, from a field point of view, the variation and rate of variation of the inclination are considered far more interesting than the relevant absolute values.

In conclusion, the study shows that a single IMU positioned on the lower back trunk provides reliable angular displacements and angular velocity in the sagittal plane during both the block start and the beginning of the pick-up phase of the sprint. The results support the possibility for coaches to be supplemented with a reliable and wearable instrument to collect information about the sprint start performance of their athletes directly in the field.

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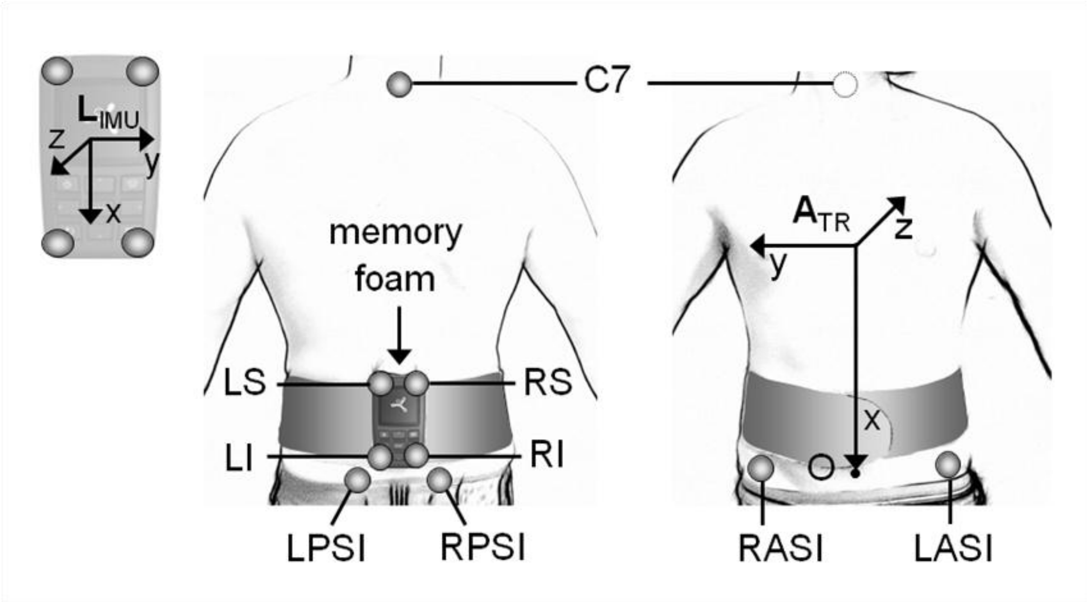

Figure 1 – IMU, belt, memory foam material, and marker location. The markers placed on the IMU (LI, LS, RI, RS), trunk (C7) and pelvis, (RPSIS, LPSIS, RASIS, LASIS) are indicated, as well as the trunk anatomical reference frame, $\mathbf{A}_{TR}$: O: midpoint between LPSIS and RPSIS; x-axis: joining C7 and O, positive downward; z-axis: directed as the vector product between the x-vector and the vector LASIS-RASIS; y-axis: orthogonal to the x-z plane.

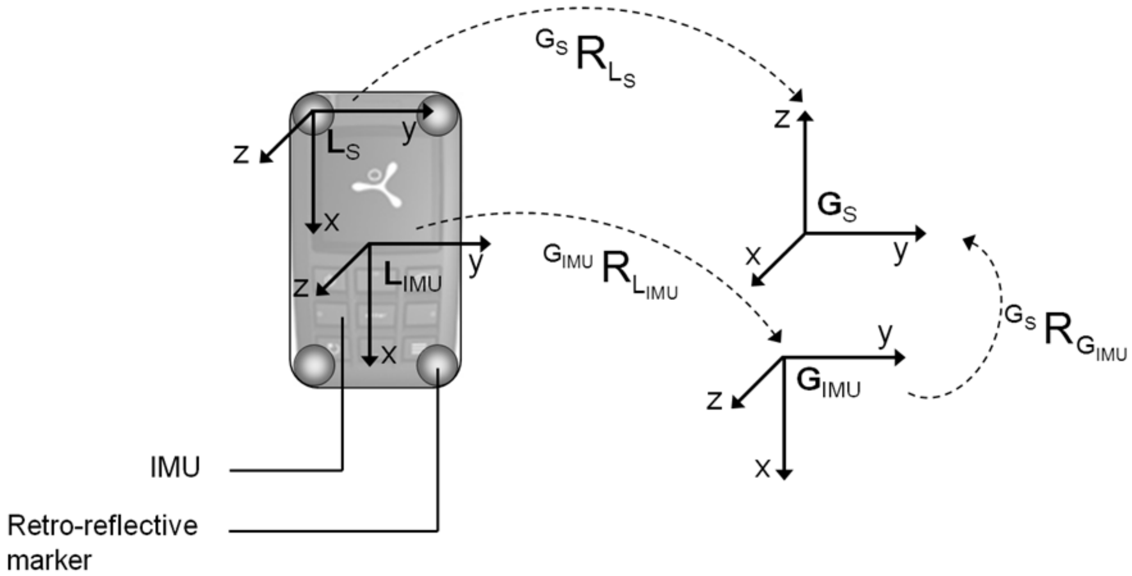

Figure 2 – Local (**L**) and global (**G**) frames for the inertial unit (IMU) and the stereophotogrammetric system (S). ${}^{G_S}R_{L_S}$: orientation of the marker frame built on the IMU (**L**$_S$) with respect to the stereophotogrammetric global reference frame (**G**$_S$); ${}^{G_S}R_{L_{IMU}}$: orientation of the local IMU frame (**L**$_{IMU}$) with respect to the IMU global reference frame (**G**$_{IMU}$); ${}^{G_S}R_{G_{IMU}}$: orientation of the IMU global reference frame (**G**$_{IMU}$) with respect to the stereophotogrammetric global reference frame (**G**$_S$).

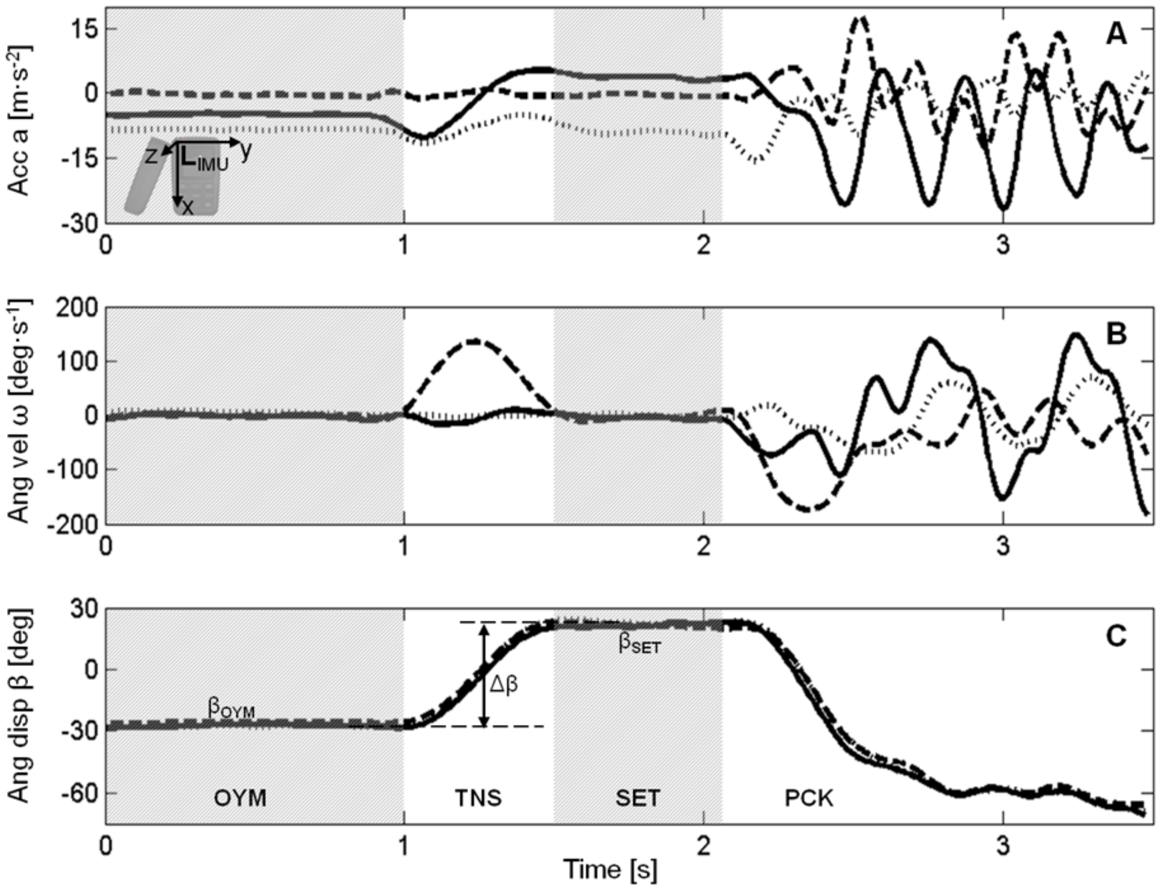

Figure 3 – Raw acceleration (A) and angular velocity (B) data, for a randomly chosen subject and trial, measured along and about the IMU local axes ($\mathbf{L}_{IMU}$, depicted in the bottom left corner of panel A: x axis (solid line), y axis (dashed line) and z axis (dotted line). Angular displacement β (C), obtained for the same subject and trial from the IMU local frame, $\mathbf{L}_{IMU}$, (solid line), from the stereophotogrammetric local frame, $\mathbf{L}_{S}$, (dashed line) and from the trunk anatomical reference frame, $\mathbf{A}_{TR}$, (dotted line). Static phases (OYM, SET, shaded intervals) and non-static phases (TNS, PCK, white intervals) are shown. The angular displacement parameters (β_{OYM}, β_{SET} and $\Delta\beta$) are also indicated. β was considered to be zero when the unit was in a horizontal position; clockwise rotations correspond to positive angles.

Table 1 – Curve similarity analysis: mean±SD of the correlation coefficient (r), the Root Mean Square Difference (RMSD) and the RMSD expressed in percentage of $\Delta\beta$ ($RMSD_{\%}$), computed to assess IMU accuracy and IMU-trunk consistency, relative to the whole task and to the PCK phase alone.

	IMU accuracy	**IMU-trunk consistency**
r	0.994 ± 0.013	0.998 ± 0.002
r_{PCK}	0.995 ± 0.015	0.998 ± 0.001
RMSD [deg]	3 ± 2	3 ± 2
$RMSD_{\%}$ [%]	4 ± 3	5 ± 3
$RMSD_{PCK}$ [deg]	3 ± 3	3 ± 2
$RMSD_{\%PCK}$ [%]	5 ± 3	6 ± 4

Table 2 – Parameter analysis: descriptive statistics (mean ± SD) of each estimated parameter and of the absolute differences between the IMU and the stereophotogrammetric sets of parameters, for both IMU accuracy ($\boldsymbol{\Delta}_{IMU}$) and IMU-trunk consistency ($\boldsymbol{\Delta}_{TR}$).

	$\mathbf{L_S}$	$\mathbf{L_{IMU}}$	$\mathbf{A_{TR}}$	**IMU accuracy**	**IMU-trunk consistency**
				$\boldsymbol{\Delta}_{IMU}$	$\boldsymbol{\Delta}_{TR}$
β_{OYM} [deg]	-29 ± 6	-29 ± 6	-29 ± 6	1 ± 1	0 ± 1
β_{SET} [deg]	12 ± 7	12 ± 6	9 ± 6	1 ± 1	4 ± 4
$\Delta\beta$ [deg]	43 ± 8	43 ± 7	39 ± 5	1 ± 1	4 ± 4
ω_{TNS} [deg/s]	98 ± 18	106 ± 19	93 ± 18	8 ± 4	4 ± 6
ω_{PCK} [deg/s]	-192 ± 29	-201 ± 25	-198 ± 31	9 ± 6	6 ± 13