

Trunk Inclination Estimate During the Sprint Start Using an Inertial Measurement Unit: A Validation Study

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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-laboratory 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

An effective start is crucial for successful sprint running performance and directly affects 60–400 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, that is, the phase ranging from block clearing to the upright position.⁹

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Such monitoring is allowed in-the-field by wearable inertial measurement units (IMUs), embedding a three-axis 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 with 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 Setup 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: 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 9-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 (G_{IMU}) was defined in a static phase aligning the x-axis of L_{IMU} with the gravity vector (Figure 2). The orientation matrix of L_{IMU} with respect to 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 nonstatic 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 that is, 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 favor 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 $t = .5$ 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 (L_S) was defined (Figure 2) and its orientation in the stereophotogrammetric global

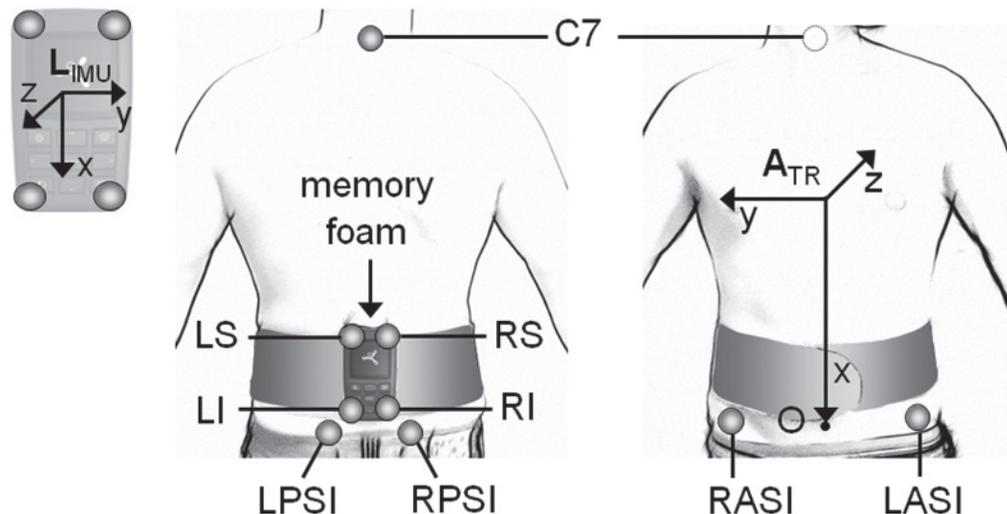


Figure 1 — IMU, belt, memory foam material, and marker location. The markers placed on the IMU (LI, LS, RI, RS), trunk (C7) and pelvis, (RPSIS, LPSIS, RASIS, LASIS) are indicated, as well as the trunk anatomical reference frame, A_{TR} : O: midpoint between LPSIS and RPSIS; x-axis: joining C7 and O, 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.

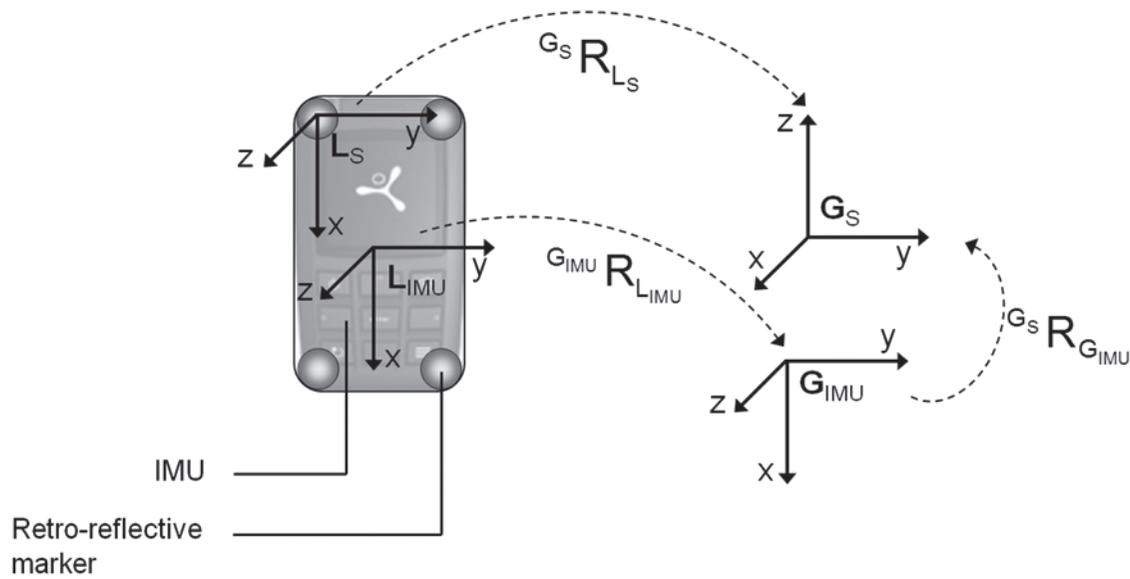


Figure 2 — Local (L) and global (G) frames for the inertial unit (IMU) and the stereophotogrammetric system (S).

${}^{G_S}R_{L_S}$: orientation of the marker frame built on the IMU (L_S) with respect to the stereophotogrammetric global reference frame (G_S);

${}^{G_{IMU}}R_{L_{IMU}}$: 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).

reference frame (G_S) was obtained in each instant of time. To compare the orientation of L_S and L_{IMU} in the same global reference frame, the latter had to be expressed with respect to G_S . To this aim, the time-invariant rotation matrix relating the stereophotogrammetric and the IMU global reference frames was calculated, assuming that L_S was coincident with L_{IMU} at time zero (Figure 2). To compare the IMU orientation with the whole trunk orientation, a trunk anatomical frame (A_{TR}) was defined (Figure 1) and its orientation with respect to G_S obtained in each instant of time. Finally, Tait-Bryant angles (axis mobile rotation sequence: yxz) were calculated with respect to G_S , from the orientation of L_{IMU} , L_S and of the whole trunk 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 L_{IMU} and L_S (IMU accuracy), and from L_{IMU} and A_{TR} (IMU-trunk consistency), was then evaluated (Δ_{IMU} and Δ_{TR}).

Statistical Analysis

To assess both IMU accuracy and IMU-trunk consistency, the β curve as obtained from L_{IMU} was compared with

those obtained from L_S and A_{TR} , respectively. To this aim, the difference between β_{OYM} obtained from the L_{IMU} and A_{TR} was computed ($\beta_{OFF} = 18 \pm 4$ 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. The 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 \pm SD) was performed (SPSS Inc. 17.0, Chicago, IL, USA; $\alpha = .05$). Moreover, to assess the agreement between IMU and stereophotogrammetry, Bland-Altman analysis of Δ_{IMU} and Δ_{TR} was performed,^{25,26} and the absence of heteroscedasticity²⁷ was verified.

Results

For the IMU accuracy, β curves from L_{IMU} and L_S presented a $RMSD_{\%}$ lower than $4 \pm 3\%$ 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).

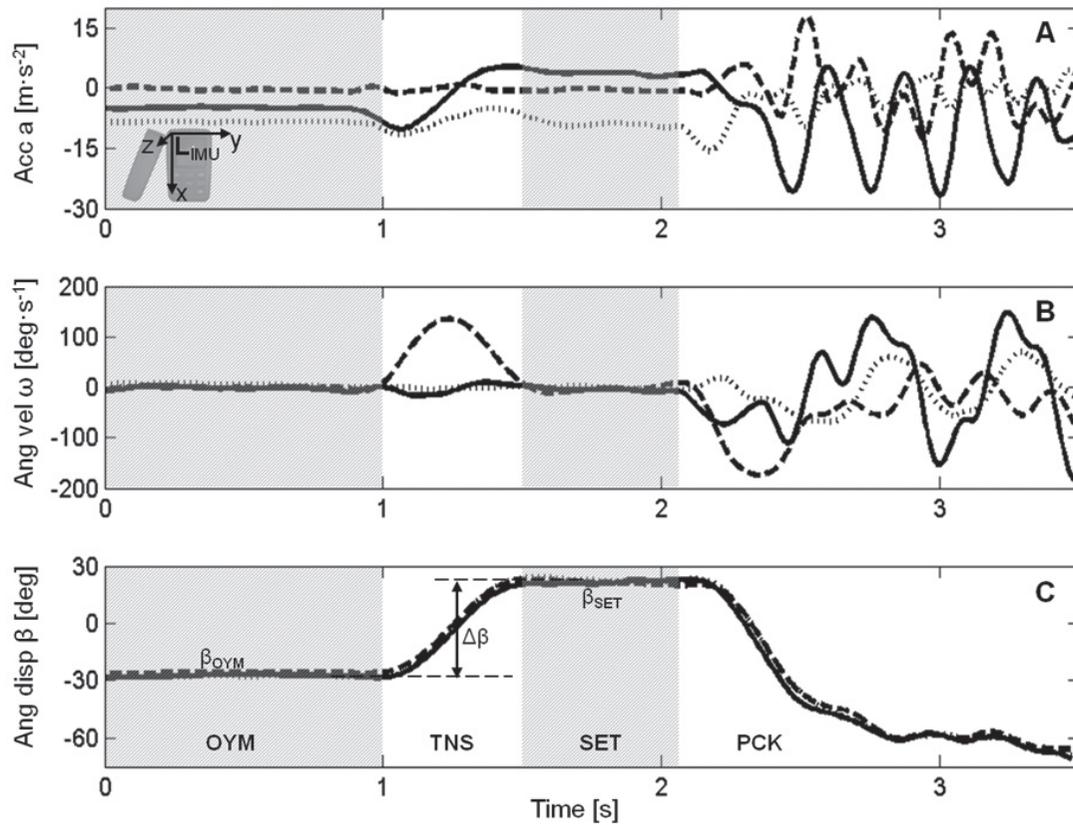


Figure 3 — Raw acceleration (A) and angular velocity (B) data, for a randomly chosen subject and trial, measured along and about the IMU local axes (L_{IMU} , depicted in the bottom left corner of panel A: x axis (solid line), y axis (dashed line) and z axis (dotted line)). Angular displacement β (C), obtained for the same subject and trial from the IMU local frame, L_{IMU} , (solid line), from the stereophotogrammetric local frame, L_S , (dashed line) and from the trunk anatomical reference frame, A_{TR} , (dotted line). Static phases (OYM, SET, shaded intervals) and nonstatic 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 \pm 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

All parameters and absolute differences proved to be normally distributed. While all estimated parameters differed among athletes ($P < .001$), no statistical differences resulted for Δ_{IMU} and Δ_{TR} ($P > .15$). Δ_{IMU} and Δ_{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 Δ_{IMU} and Δ_{TR} for ω_{PCK} were found to be lower than 9 and 6 $\text{deg}\cdot\text{s}^{-1}$, and decreased to 8 and 4 $\text{deg}\cdot\text{s}^{-1}$ 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 Δ_{IMU} and Δ_{TR} was observed for all estimated parameters, indicating that no systematic error was present. Moreover, no heteroscedasticity was found for all parameters included in Δ_{IMU} and Δ_{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 current study athletes were forced to complete the task in a relatively short distance, the average peak angular velocity of the trunk (A_{TR} : $\omega_{PICK-UP} = 198 \pm 31 \text{ deg}\cdot\text{s}^{-1}$) was comparable with previous literature results^{7,13} ($170 \pm 60 \text{ deg}\cdot\text{s}^{-1}$ and $186 \pm 48 \text{ deg}\cdot\text{s}^{-1}$).

Table 2 Parameter analysis: descriptive statistics (mean \pm SD) of each estimated parameter and of the absolute differences between the IMU and the stereophotogrammetric sets of parameters, for both IMU accuracy (Δ_{IMU}) and IMU-trunk consistency (Δ_{TR})

	L_S	L_{IMU}	A_{TR}	IMU Accuracy Δ_{IMU}	IMU-Trunk Consistency Δ_{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

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, ie, rigid trunk. After β_{OFF} removal, Δ_{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 β_{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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References

1. Čoh M, Tomažin K, Stuhec S. The biomechanical model of the sprint start and block acceleration. *Facta Univ Ser Phys Ed Sport.* 2006;4(2):103–114.
2. Harland MJ, Steele JR. Biomechanics of the sprint start. *Sports Med.* 1997;23(1):11–20. [PubMed doi:10.2165/00007256-199723010-00002](#)
3. Schot PK, Knutzen KM. A biomechanical analysis of four sprint start positions. *Res Q Exerc Sport.* 1992;63(2):137–147. [PubMed doi:10.1080/02701367.1992.10607573](#)
4. Fortier S, Basset FA, Mbourou GA, Faverial J, Teasdale N. Starting block performance in sprinters: a statistical method for identifying discriminative parameters of the performance and an analysis of the effect of providing feedback over a 6-week period. *J Sports Sci Med.* 2005;4(2):134–143.
5. Mero A, Komi PV, Gregor RJ. Biomechanics of sprint running - a review. *Sports Med.* 1992;13(6):376–392. [PubMed doi:10.2165/00007256-199213060-00002](#)
6. Kugler F, Janshen L. Body position determines propulsive forces in accelerated running. *J Biomech.* 2010;43(2):343–348. [PubMed doi:10.1016/j.jbiomech.2009.07.041](#)
7. Slawinski J, Bonnefoy A, Ontanon G, et al. Segment-interaction in sprint start: analysis of 3D angular velocity and kinetic energy in elite sprinters. *J Biomech.*

- 2010;43(8):1494–1502. PubMed doi:10.1016/j.jbiomech.2010.01.044
8. Mero A, Komi PV. Reaction-time and electromyographic activity during a sprint start. *Eur J Appl Physiol Occup Physiol.* 1990;61(1-2):73–80. PubMed doi:10.1007/BF00236697
 9. Jones R, Bezodis I, Thompson A. Coaching sprinting: expert coaches' perception of race phases and technical constructs. *Int J Sports Sci Coaching.* 2009;4(3):385–396. doi:10.1260/174795409789623964
 10. Slawinski J, Bonnefoy A, Leveque JM, et al. Kinematic and kinetic comparisons of elite and well-trained sprinters during sprint start. *J Strength Cond Res.* 2010;24(4):896–905. PubMed doi:10.1519/JSC.0b013e3181ad3448
 11. Čoh M, Jošt B, Škof B, Tomažin K, Dolenc A. Kinematic and kinetic parameters of the sprint start and start acceleration model of top sprinters. *Acta Univ Carol Gym.* 1998;28:33–42.
 12. Mero A, Luhtanen P, Komi PV. A biomechanical study of the sprint start. *Scand J Sport Sci.* 1983;5:20–28.
 13. Natta F, Decker L, Boisnoir A. Caractérisation des comportements posturo-cinétiques en sprint. Paris:INSEP. Rapport du projet de recherche MJSVA n° 03-006. <http://195.154.95.153:81/archimede/ExploreOneUpload.do?sessionId=C4906B0B3D453D1195C326817AAC1576?vref=664>. Published 2006. Accessed May 22, 2012.
 14. Purcell B, Channells J, James D, Barret R. Use of accelerometers for detecting foot-ground contact time during running. *Proc. SPIE.* doi:10.1117/12.638389
 15. Bergamini E, Picerno P, Pillet H, Natta F, Thoreux P, Camomilla V. Estimation of temporal parameters during sprint running using a trunk-mounted inertial measurement unit. *J Biomech.* 2012;45(6):1123–1126. PubMed doi:10.1016/j.jbiomech.2011.12.020
 16. Channels J, Purcell B, Barrett R, James D. Determination of rotational kinematics of the lower leg during sprint running using accelerometers. *Proc. SPIE.* doi:10.1117/12.638392
 17. Faber GS, Kingma I, Bruijn SM, van Dieen JH. Optimal inertial sensor location for ambulatory measurement of trunk inclination. *J Biomech.* 2009;42(14):2406–2409. PubMed doi:10.1016/j.jbiomech.2009.06.024
 18. Wong WY, Wong MS. Trunk posture monitoring with inertial sensors. *Eur Spine J.* 2008;17(5):743–753. PubMed doi:10.1007/s00586-008-0586-0
 19. Forner-Cordero A, Mateu-Arce M, Forner-Cordero I, Alcantara E, Moreno JC, Pons JL. Study of the motion artefacts of skin-mounted inertial sensors under different attachment conditions. *Physiol Meas.* 2008;29(4):N21–N31. PubMed doi:10.1088/0967-3334/29/4/N01
 20. Liu W, Nigg BM. A mechanical model to determine the influence of masses and mass distribution on the impact force during running. *J Biomech.* 2000;33(2):219–224. PubMed doi:10.1016/S0021-9290(99)00151-7
 21. Sabatini AM. Quaternion-based extended Kalman filter for determining orientation by inertial and magnetic sensing. *IEEE Trans Biomed Eng.* 2006;53(7):1346–1356. PubMed doi:10.1109/TBME.2006.875664
 22. Jurman D, Jankovec M, Kamnik R, Topic M. Calibration and data fusion solution for the miniature attitude and heading reference system. *Sens Actuators A Phys.* 2007;138(2):411–420. doi:10.1016/j.sna.2007.05.008
 23. Favre J, Jolles BM, Siegrist O, Aminian K. Quaternion-based fusion of gyroscopes and accelerometers to improve 3D angle measurement. *Electron Lett.* 2006;42(11):612–614. doi:10.1049/el:20060124
 24. Mazzà C, Donati M, McCamley J, Picerno P, Cappozzo A. An optimized Kalman filter for the estimate of trunk orientation from inertial sensors data during treadmill walking. *Gait Posture.* 2012;35(1):138–142. PubMed doi:10.1016/j.gaitpost.2011.08.024
 25. Bland JM, Altman DG. Agreement between methods of measurement with multiple observations per individual. *J Biopharm Stat.* 2007;17(4):571–582. PubMed doi:10.1080/10543400701329422
 26. Atkinson G, Nevill AM. Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med.* 1998;26(4):217–238. PubMed doi:10.2165/00007256-199826040-00002
 27. Nevill AM, Atkinson G. Assessing agreement between measurements recorded on a ratio scale in sports medicine and sports science. *Br J Sports Med.* 1997;31(4):314–318. PubMed doi:10.1136/bjism.31.4.314
 28. Cohen J. *Statistical power for the behavioral sciences.* 2nd ed. Hillsdale, NJ: Lawrence Erlbaum Associates; 1988:75–105.
 29. Bobbert MF, Van Soest AJ. Effects of muscle strengthening on vertical jump height: a simulation study. *Med Sci Sports Exerc.* 1994;26(8):1012–1020. PubMed

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