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ESTIMATE OF TRUNK INCLINATION DURING FAST MOVEMENTS BY INERTIAL SENSING

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The purpose of this study was to identify a reliable algorithm to estimate the inclination of a trunk-mounted inertial measurement unit (IMU) during fast movements and to test its subject- and task-specificity. Ten amateur football players performed three times the approach phase of the drive block technique and a fast sit-to-stand-to-sit task. IMU data were processed using an *ad hoc* adaptive Kaman filter, and pitch angular displacements were obtained and compared to stereophotogrammetric reference estimates. Tuning of the algorithm parameters was performed and relevant accuracy was tested in terms of root mean squared difference (RMSD) and correlation coefficient. Strong correlation (>0.978) were observed for both motor tasks, together with RMSD smaller than 4.4±1.7 deg. The tuned algorithm proved to be neither subject- nor task-specific (p>0.05).

KEY WORDS: orientation, inertial measurement unit, Kalman filter, American football.

INTRODUCTION: A successful coaching outcome is related to objective performance monitoring, evaluation and training planning. Quantitative assessment of mechanical variables that determine performance, or are related to injury risk, could support this process. In this respect, information about the orientation of body segments is essential for technique analysis as well as for investigating, and thus preventing, risky postures (Lees, 2002).

In American football, for example, trunk inclination, along with limb joint angles can be critical for linear momentum transfer to the opponent (Hay, 1983). In rowing, the correct timing of legs and trunk movement is crucial to maximize stroke power (Kleshnev, 2006), while during the sprint start, trunk orientation is considered one of the key elements in moving from the crouch to the upright position without decreasing horizontal velocity (Jones et al., 2009). At the same time, trunk inclination may influence the risk of injury at the spine as it plays a role in modifying spine load conditions. In American football, for example, it influences how forces are transmitted along the vertical axis of the cervical spine, the structures of which can be injured when contact occurs with the head, neck, and trunk in alignment (Torg et al., 2002). During execution of the half squat, trunk bending is the factor that most influences the compression load in the lumbar area (Cappozzo et al., 1985).

The assessment of body segment orientation is best performed infield, where the athletes push themselves to the limit during training and competition. Replicating the athlete performance during quantitative evaluation allows maximization of testing accuracy. In this framework, the new generation of magneto-inertial measurement units, which are portable, cheap, and easy-to-use, allows activities to be performed in real situations, and opens new perspectives in sport science. Movement-related measures, which enable estimation of the unit orientation, can be based on the use of magneto-inertial sensors, or can rely on inertial measurements (linear acceleration and angular velocity) only. Robustness and reliability of these estimates depends highly on the signal to noise ratio and on the duration of the task. In this respect, the analysis of sport tasks is more challenging than that of everyday life activities, because the explosiveness of the former can cause greater movement artefacts of the unit relative to the skeleton, thus increasing the noise. This artefact was shown to be subject-dependent and sensitive to the site and method of unit attachment (Forner-Cordero et al, 2008). Together with gyroscope drift, which can cause large integration errors, it may jeopardize the consistency of the orientation estimates. Sensor-fusion algorithms for orientation estimation can compensate these errors, fusing information derived from gyroscopes and accelerometers, by integrating the measured angular velocity and estimating the unit inclination from the measured acceleration, respectively (Sabatini 2011). These algorithms are often embedded in commercial devices or may be implemented based on the state of the art (Sabatini, 2012, Mazzà et al, 2010). The accuracy of the cited methods may depend on a task-related tuning of relevant algorithm parameters.

So far, inertial measurement units (IMUs) have been used to estimate trunk or lower limb segments orientation during sports such as swimming (Dadashi et al, 2012), squat lifting (Camomilla et al, 2010), skydiving (Wixted & James 2011), sprint start (Bergamini et al, 2012), alpine skiing (Brodie et al, 2008), and freestyle snowboarding (Kruger et al, 2009). Nevertheless, only a few of the published methods have been specifically developed and tested, or the built-in algorithms validated, for the fast movements typical of sport activities.

The purpose of this study was, therefore, to identify a reliable algorithm to estimate the inclination of a trunk-mounted IMU, which could be used for the estimation of performance related angles during fast movements. To this aim, a set of tasks characterized by high accelerations of the trunk were performed by amateur athletes; IMU data were acquired and validated against reference measurements provided by a stereophotogrammetric system. Tuning of the algorithm parameters was performed on half of the participants, and the robustness of relevant parameters was tested in terms of task- and subject-specificity.

METHODS: *Experimental set up and data acquisition.* Ten male amateur football players (mass: 88±20 kg; stature: 1.81±0.10 m) took part in the study and gave their written informed consent. After 10 minutes warm up, each athlete performed 3 times the approach phase of the drive block technique of American football and 3 times a fast sit-to-stand-to-sit task. Each subject was equipped with an IMU (FreeSense, Sensorize Ltd - 200 frames/s) containing a 3D accelerometer and a 3D gyroscope (±6 g and ±500 deg/s full-range scale, respectively). The unit provides data with respect to a local sensor-embedded frame coinciding with the geometrical axes of the IMU case. IMU data were sent via Bluetooth® to a computer. Careful attention was paid to the fixation of the IMU to the athletes' body, to reduce the unit oscillations relative to the underlying bone, without limiting the athlete's movements. The IMU was positioned with an *ad hoc* elastic belt on the lower back trunk at L2 level, and avoiding the low lumbar area, which is more affected by the wobbling of soft tissue masses. To validate IMU-based estimates, a nine-camera stereophotogrammetric system (Vicon MX - 100 frames/s) was used. Four markers were attached to the IMU to determine the unit orientation. A sudden trunk flexion-extension from standing was performed at the beginning of each trial and peak angular velocity was used to synchronize the signals.

Data processing: data were low-pass filtered using a 2^{nd}-order zero-lag Butterworth filter. A trial-specific cut-off frequency (5-6 Hz) was determined using a residual analysis (Winter, 1990). The orientation of the IMU local frame ($\mathbf{L}_{IMU}$) with respect to the IMU global frame was estimated through an adaptive Kalman filter (Mazzà et al, 2010), *ad hoc* designed to obtain the unit inclination by selecting the information provided by accelerometers and gyroscopes. To run the filter, the values of five parameters must be set: q and r, which are the static noises associated to the gyroscope and the accelerometer, respectively; s_1, s_2 and m, which are three constants defining a weighting coefficient that increases or decreases r, according to the state of the system. To obtain reference values, a photogrammetric local frame ($\mathbf{L}_S$) was defined using the four markers attached on the IMU and its orientation in the photogrammetric global frame ($\mathbf{G}_S$) was obtained. To compare the orientation of $\mathbf{L}_S$ and $\mathbf{L}_{IMU}$ in the same global frame, the latter was expressed with respect to $\mathbf{G}_S$ through an *ad hoc* experiment. Finally, Tait–Bryant angles (axis mobile rotation sequence: yxz) were calculated from the orientation of $\mathbf{L}_{IMU}$ and $\mathbf{L}_S$. The rotation about the medio-lateral y axis, pitch, was further considered. Pitch angles obtained from IMU data using the Kalman filter were compared to the corresponding reference angles.

To test whether algorithm tuning was subject- and/or task-dependent, subjects were divided into two homogeneous subgroups (a tuning and a validation group) using a balanced randomization procedure, by sorting them in ascending order according to their waist

circumference (0.88±0.09 m) and alternatively assigning them to one of the two groups. Data from the drive block performed by the tuning group were used to estimate the parameters of the Kalman filter. The *lsqnonlin* algorithm (Matlab®, Mathworks, Natick, MA) was used to determine the parameters by minimizing the RMSD (root mean square difference) between reference and estimated pitch angular displacements, as the cost function.
Statistical analysis: To test the accuracy of the tuned algorithm, the RMSD and Pearson's correlation coefficient (cc) between the pitch curves obtained from $\mathbf{L}_S$ and $\mathbf{L}_{IMU}$ were calculated. Subject- and task-specificity of the tuned algorithm was tested using a repeated-measures two-way ANOVA (factors: task, group; α=0.05) on RMSD between:

- the drive blocks of the tuning and validation groups (subject-specificity),
- the drive block and the sit-to-stand-to-sit of the tuning group (task-specificity).

Table 1
RMSD and r results

Group	Motor task	RMSD [deg]	cc
Tuning	Drive block	4.1±1.3	0.996±0.001
Validation	Drive block	4.4±1.7	0.995±0.002
Tuning	Sit-to-stand-to-sit	3.8±1.7	0.978±0.004
Validation	Sit-to-stand-to-sit	3.0±1.7	0.989±0.007

subject-specificity
task-specificity

RESULTS: RMSD and cc results for the drive block and the sit-to-stand-to-sit tasks are reported for both groups (Table 1). Results were not correlated with the randomization variable. The tuned values of the Kalman filter parameters were: q=3.2e^{-7} deg/s, r=1.12e^{-6} m/s^2, s_1=-1.98 m/s^2, s_2=-1.27 m/s^2, m=90. The corresponding RMSD of the tuning group during the drive block was 4.1±1.3 deg, with high correlation coefficients (cc=0.996±0.001). Similar values were observed for the validation group. Results for the sit-to-stand-to-sit exhibited slightly smaller RMSD (<3.8±1.7 deg), probably due to the lower velocities characterizing this task (81±26 deg/s on average compared to 198±66 deg/s for the drive block). However, ANOVA analysis showed no significant differences between subjects and tasks, indicating that the results of the tuned algorithm are neither subject- nor task-specific.

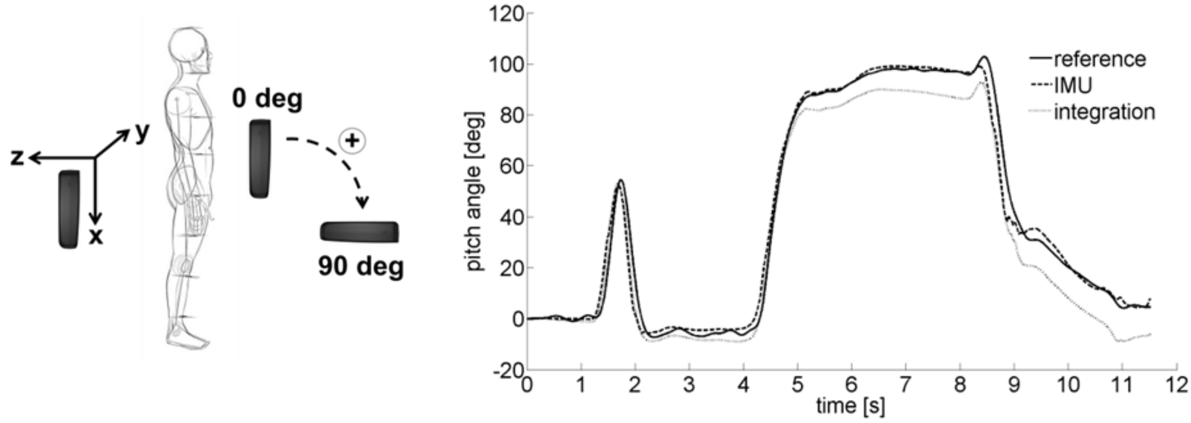

Figure 1: Pitch angle during the approach phase of the drive block technique for a randomly chosen trial and subject. Reference (solid line), IMU-based (dashed line), and simple integration of the angular velocity (dotted line) estimates are reported.

DISCUSSION: A sensor fusion algorithm for the estimate of the inclination of a trunk-mounted IMU was tuned for fast movements, and the absence of task- and subject- specificity of relevant parameters shown. Of particular note, is that results were not sensitive to the amount of soft tissues, which were quite different among participating athletes (BMI=21.06-3.38 kg/m^2). Comparison between the pitch angles as obtained by numerical integration of the IMU angular velocity and by using the Kalman filter proved that sensor fusion is essential when estimating body segment orientation. The gyroscope drift, in fact, causes large integration errors even when the analyzed motor tasks have a very short duration, as is the case for the movements considered in the present study (over 10 deg drift error in 10 s) (Figure 1). To fully test the accuracy of the tuned algorithm, a validation of the orientation estimates during long duration movements needs to be performed, together with a sensitivity analysis to determine the importance of selecting the correct parameters for the Kalman filter. Moreover, the IMU artefact movements relative to the skeleton, which cannot be compensated for by fusion algorithms, remain to be taken into account when estimating performance or injury related variables, related to body segment and not to IMU orientations.

CONCLUSION: This study identified a reliable algorithm to estimate the inclination of a trunk-mounted IMU, which can be used for the estimation of performance related angles during fast movements. Investing resources in this aspect of sports science is crucial to provide coaches with more reliable information about the orientation in space of body segments which is essential for technique analysis as well as for preventing risky postures.

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