INERTIAL SENSOR FEEDBACK DURING SQUAT EXERCISE

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The half-squat is the most widely used exercise in the resistance training, which must be considered optimal only if it is specific and safe. Safeness relies, with other factors, in using the correct technique and being provided with adequate monitoring and feedback. In this perspective, this study a) provided a thorough characterization of the less dangerous squat technique, and b) showed how wearable inertial measurement units (IMU) can be used to quantify key variables useful to reduce errors. The IMU estimate presented a good concurrent validity (r=0.91) for trunk maximal forward inclination, although with significant mean systematic bias of 7±5 deg, and fair concurrent validity for pelvis and barbell rotations in the frontal plane with lower systematic biases. Thus the use IMUs to provide practitioners a quantitative feedback of the execution is encouraged.

KEY WORDS: inertial measurement unit, monitoring, half-squat technique

INTRODUCTION: The so-called half-squat is probably the most used training mean in the development of lower limbs muscular efficiency during physical activity and sports. Despite its undisputed efficacy in this respect, a training program based on overloads can not be considered optimal if it is not, at the same time, specific and safe. In the authors' opinion, safeness relies on the combination of several key elements: a prepared, wise, and careful trainer, a grown and evolved athlete, a controlled and correct technical execution and an appropriate assistance. In particular, technique, certainly along with other factors, may determine differences in the level of risk involved (Aaberg 2000).

Different body structures are involved in this multi-joint exercise, the vertebral column being the most overloaded and thus, most at risk. A slight forward lean of the trunk, due to hip flexion, paralleled by trunk extensor moments, characterizes the half-squat (Wretenberg et al. 1996). This lean should be controlled so that stress on the lumbar spine is kept to a minimum (Neitzel, Davies 2000). In fact, it is known that trunk bending is the factor that most influences the compression load on the lumbar area during execution of the half squat (Cappozzo et al., 1985) and that compressive (Braidot et al., 2007; Zatsiorky and Kraemer 2008) and shear forces (Braidot et al., 2007) as well as intradiscal pressure (Adams and Dolan, 1995) increase for increasing inclinations of the trunk thus amplifying the risk of injury. Nevertheless, papers describing possible "correct" techniques for the trunk movement (Braidot et al. 2007; Kritz et al. 2009) paid limited attention to the assessment of relative risks. Aside from flexion-extension, torsional and lateral bending movements may as well damage of the spine (Adams & Dolan, 1995). Crucial, in this respect, is barbell control. Its asymmetric placement or a poor control of the free weights may lead to swings from side to side as the person tries to lift them, and to a malalignment of the entire column, resulting in the application of considerable and not well-controlled lateral bending forces to the spine.

Thus, to maximize safety, due importance must be given to monitoring that the correct technique is carried out. A measure of movement-related data could contribute in monitoring the exercise and as an aid in correcting errors, as far as the relevant setup is kept simple and allows the subject to perform his/her activity in the real setting. In this respect, wearable inertial measurement units (IMU), that provide accelerations and angular velocities, seem a proper instrument for safety monitoring, while being able to provide information on performance related aspects such as strength and power. Although in recent years the availability of wearable IMUs opened new perspectives in sport sciences, no study, to the authors' knowledge, considered them in this perspective.

A better description of the technique is necessary and central to the development of any technology-based feedback system. Such aid could be fully exploited only if well rooted in a preliminary qualitative analysis guiding the identification of the most appropriate quantitative parameters. The purpose of this study is, to verify the feasibility of using IMUs to provide feedback to practitioners performing the squat exercise through the following steps: a) characterize the techniques less dangerous and as complete as possible, b) identify common errors, potentially dangerous, c) identify parameters, measurable using inertial sensors, that can be used by practitioners to monitor and, possibly, reduce execution errors, and d) test the reliability of these parameters against reference measures.

METHODS: Characterization of half-squat technique. The following technical description was determined, based on a careful and exhaustive analysis of the literature (O'Shea 1985; Aaberg 2000; Escamilla 2001; Braidot et al. 2007; Comfort & Kasim 2007; Zatsiorsky & Kraemer 2008; Kritz et al. 2009 , Paoli et al. 2009), and used in the experimentation:

Preparatory position: slight extension at the thoracic spine level, scapulae adducted, slightly lift the chest, without forcing the flattening of the lumbar spine.
Barbell: on trapezius and rear deltoids just below C7.
Grip: slightly wider than the shoulders, thumbs blocking the fingers, wrists in slight dorsal extension.
Head and neck: in natural position, gaze straight.
Thoracic spine: slightly extended.
Lumbar spine: natural and stable position, avoiding excessive flexion/extension.
Increase intra-abdominal pressure: abdominal muscle contraction, breath control (before - forced inspiration, descent phase - breath-held, end of the ascending phase - out) and use weight lifter's support belt.
Pelvis: stable, avoid excessive tilt.
Knees: do not exceed 80-90 deg flexion, stable, avoid lateral-medial movements, restrict the antero-posterior ones, maintain knee and toes in alignment.
Feet: flat and stable, width slightly greater than that of the pelvis, externally rotated by 20-30 deg, heels in contact with the ground at all times.

Experimental study: Twelve male subjects (24±2 years, 73±7 kg, 1.79±0.06m), not sedentary, with previous knowledge of the task, and without clinically significant injuries at the most stressed joints, volunteered for this study, after signing an informed consent. The subjects were asked to perform the described technique, wearing a weightlifting belt during a test, for the determination of their maximum load (1RM, 5-6 tests, max 2 reps) and an incremental load test (set at 20,40,60,80% 1RM, repetitions performed for 8,6,4,2 times, respectively). 3D acceleration and angular velocities of the trunk were acquired at 100Hz by a wearable inertial sensor equipped with an on board data logger (Freesense, Sensorize, Italy), fixed onto the weightlifting belt (L2-L4 level). Barbell, trunk, and pelvis kinematics were measured acquiring at 100 Hz the kinematics of the spinous processes of C7, S1, anterior and posterior superior iliac spines, and the extremities of the barbell with a nine cameras stereophotogrammetric system (Vicon MX, Oxford, UK), Figure 1.

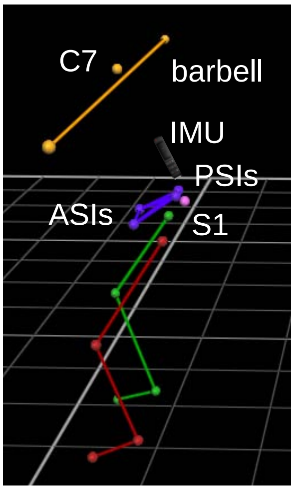

Figure 1: Marker and IMU placement.

Data analysis: Data analysis was performed using Matlab software (MathWorks®, USA). The movement of barbell, pelvis, and trunk, assumed to be a rigid segment, were analysed in the sagittal, frontal, and coronal plane. Acceleration and angular velocity measures, provided by the IMU with respect to a moving reference frame, were independently determined and analysed. When the sensor's inertial acceleration was close to zero, the accelerometer measured the inclination of the sensor relative to gravity. Conversely, when the sensor underwent a motion that generated inertial accelerations, the orientation angles were estimated integrating the angular velocity signal provided by the gyroscopes. A quaternion based algorithm (Favre et al., 2006) and a Kalman filter were implemented in order to compute trunk orientation angles relative to a global reference frame (pitch → sagittal plane, roll → frontal plane). Yaw (→ transverse plane) was provided with respect to the posture. Qualitative analysis for potentially dangerous error identification was performed by visual inspection of the 3D reconstruction of marker trajectories. On the sagittal, frontal, and coronal planes, the rotations and their agreement with the proposed technique were observed. Although the kinematic analysis could be performed with more markers on various technical elements related to the proposed technique, results will be given only for the errors for which it is hypothesised that an inertial sensor on the belt could provide a feedback (barbell, trunk, and pelvis rotation). Each qualitative error was associated to an angle for both kinematics and inertial sensor data, Table 1. For all angles listed in Table 1 the maximal peak for each repetition was used as a quantitative parameter. Trunk orientation in the sagittal plane was assessed at the beginning (minimum) and the end (maximum) of the descending phase.

Table 1 Qualitative description of the main errors and description of the relevant angles selected for IMU and stereophotogrammetric quantification.

Segments	*Qualitative description*	*IMU*	*Stereophotogrammetry*
Barbell	rotation on the frontal plane	roll	inclination with respect to the horizontal plane
	rotation on the transverse plane	yaw	rotation with respect to the reference medio-lateral axis
Trunk	tilt on the sagittal plane	pitch	C7-S1 vector: tilt on the sagittal plane (0° when vertical)
Pelvis	frontal lifting/drop	roll	midPSIs-midASIs vector: inclination on the frontal plane
	rotation on the transverse plane	yaw	midPSIs-midASIs vector: rotation in the transverse plane

The reliability of the parameters provided by the IMU was analysed against reference measures (stereophotogrammetry) with the following statistical analysis, performed using SPSS (version 17.0): 1) Descriptive statistics (Mean ± standard deviation); 2) Error (Stereo-IMU) description through mean bias; 3) Association between reference and IMU as the Mean ± standard deviation of the correlation coefficients of each subject (Pearson); 4) Test of normal distribution of the error with the Shapiro-Wilk test ($p>0.05$); 5) Presence of a linear trend between the amount of random error and the measured values (heteroscedasticity) investigated through inspection of Bland–Altman plots and correlation analysis; 6) If non normal or heteroscedastic, data were logarithmic (natural) transformed prior to agreement statistics; 7) Differences, between IMU and reference values and the effect of the load were ascertained by means of a 2-way fully repeated ANOVA.: 4 (load) x 2 (methods); 8) When load had no significant effect on variables, absolute reliability for repeated measurement was assessed in terms of Limits of Agreement (Bland & Altman, 2007).

Table 2 Descriptive statistics (Mean ± sd) for the two methods and for their difference and agreement analysis (Correlation coefficients and Limits of Agreement).

	sagittal plane		*frontal plane*		*transverse plane*	
Method	*Trunk (bent)*	*Trunk (standing)*	*Barbell*	*Pelvis*	*Barbell*	*Pelvis*
Stereo	36±4 deg	17±1 deg	3±1 deg	9±3 deg	3±1 deg	14±5 deg
IMU	29±7 deg	4±4 deg	4±2 deg		3±2 deg	
Stereo-IMU	7±5 deg	13±4 deg	-2±2 deg	5±3 deg	-1±2 deg	10±4 deg
Correlation	0.91±0.11	0.67±0.37	0.63±0.37	0.75±0.34	0.43±0.26	0.40±0.31
Limits of Agreement	-3.7÷17.3	-21.7÷-3.6	-1.5÷5.5	-	-3.3÷4.7	-19.3÷-1.5

RESULTS: Descriptive statistics of the measures and of the error and correlation analysis are given in Table 2. Since most of the data presented non normal distribution and heteroscedasticity was revealed for maximal trunk inclination, data were log transformed. All parameters, except for barbell rotation in the transverse plane, differed significantly ($p<0.01$), when measured with the two systems. Pelvic rotations on the frontal plane were dependent from load ($p=0.028$).

DISCUSSION: The agreement of IMU and stereophotogrammetry in determining key trunk and pelvis angles during squat was evaluated. The IMU estimate presented a good concurrent validity ($r=0.91$) for trunk maximal forward inclination, although with significant mean systematic bias of 7±5 deg. Fair concurrent validity was shown for pelvis and barbell rotations in the frontal plane with lower systematic biases. In both cases, bias can mainly be attributed to the different portion of the body whose rotation is being measured. For increasing trunk inclination, the difference between systems decrease; this effect may be explained considering that the inclination of the C7-S1 segment, assumed to be rigid with the trunk, can increase due to an increased kyphosis that, in turn, entails a decrease in lumbar lordosis, which reduces the inclination of the L2-L4 portion and, thus, of the IMU.

CONCLUSION: The half-squat, so widely used, requires careful monitoring and extreme competence of coaches and athletes. The technique proposed, which aims to reduce the risks of the exercise, is therefore the primary result. The validity of the IMU estimate of maximal trunk inclination encourages in using such device to provide the athlete and his/her coach a quantitative feedback of the execution; helping them to improve the technique and potentially increasing their awareness about the risks related to this dangerous exercise.

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