VALIDATION OF AN INERTIAL MEASUREMENT UNIT BASED ESTIMATION OF TRUNK MOTION IN SIT-SKIING: A PILOT STUDY

Cecilia Severin[1], Jan Kocbach[1], Gertjan Ettema[1], Jørgen Danielsen[1]

[1]Department of Neuromedicine and Movement Science, Centre for Elite Sports Research, Norwegian University of Science and Technology, Trondheim, Norway

Sagittal plane trunk movement is important for producing propulsive force when sit-skiing. We aimed to validate the use of inertial measurement units for measuring sagittal plane trunk movements during sit-skiing in the field. Able-bodied participants (n=4) performed 30 seconds of sit-skiing in a kneeling position on a treadmill while one AdMos IMU sensor (on the upper back) and 4 reflective markers on the trunk recorded kinematics. A secondary validation was performed with 4 sensors and markers attached to a rigid body, which was rotated to mimic the trunk during sit-skiing. For the rigid body, the root mean square error was <0.5° for the max and min angle, and range of motion, while the mean absolute percentage error was <1.6%. For the trunk, these values were <3.6° and <16.2%. AdMos IMU sensors can be used in the field to provide an estimation of the trunk motion during sit-skiing.

KEYWORDS: Para-sport, cross-country skiing, wearable technology.

INTRODUCTION: In sitting Para-Nordic skiing, athletes compete in a seated position and thus rely predominantly on arms and trunk for propulsion (Ohlsson & Laaksonen, 2017). Depending on the type and level of the disability, sit-ski athletes have different amount of trunk function, e.g., an athlete with amputated lower extremities may have full function of their trunk and hips, while an athlete with a high spinal cord injury may have very limited trunk function. Research has shown increased trunk motions during sit-skiing with increased work rates (Bjerkefors et al., 2013), and omitting the trunk from the double poling (DP) action reduces the power output (Hegge et al., 2016). It is therefore likely that athletes with larger trunk function are able to produce higher speeds than those with lower trunk function, and thus, trunk function is one of the items assessed during classification (Rosso et al., 2018). However, the classification process assesses trunk function in clinical settings, and it is difficult to estimate the degree of trunk function an athlete utilizes during sit-skiing in the field based on clinical assessments.

The use of inertial measurement units (IMUs) has become popular for quantifying human movement and is frequently used in both sport and clinical settings (e.g., Brice et al., 2018). Several studies have assessed the agreement between IMUs and traditional motion capture (MC) systems (e.g., Brice et al., 2018; Guo & Xiong, 2017; Saber-Sheikh et al., 2010), and while these results generally have been positive, researchers have highlighted that the accuracy of IMUs is both task- and segment-specific (Lebel et al., 2017; Robert-Lachaine et al., 2017). One cannot therefore assume sufficient accuracy of IMUs to estimate movements for certain tasks without further validation. However, due to their portability and low-cost, IMUs remain a valid option for many settings where movement analysis is of interest.

It is possible that equipping athletes with an IMU sensor can be used to estimate the trunk motion during sit-skiing, and potentially constitute a valuable tool for classifiers. This pilot study therefore aimed at validating the use of IMUs to measure trunk motion during sit-skiing.

METHODS: The participants (n=4) performed 30 seconds of sit-skiing in a kneeling position on a motorized treadmill (Forcelink Technology, Culemborg, The Netherlands) at 10 km/h and 0.5% incline and at 4 km/h at 5.0% incline. An IMU sensor (AdMos, ASI, Lausanne, Switzerland, 35 g) recording at 200 Hz was placed in a pocket on the upper back of a tightfitting sports-bra worn by the participants. We used an optoelectronic motion capture (MC) as the reference with 4 retroreflective markers placed on the trunk according to the ISB recommendations for the thoracic segment (henceforth referred to as ‘trunk’): the spinous process of the 7th Cervical vertebrae and the 8th Thoracic vertebrae, the Incisura Jugularis, and the Processus Xiphiodeus (Wu et al., 2005) and captured using an 11-camera MC system (Qualisys AB, Gothenburg, Sweden) recording at 100 Hz.

Since the participants were able-bodied with limited prior experience with sit-skiing, the data was collected following a familiarization period where the participants spent several minutes of double-poling (DP) in the sit-ski on the treadmill.

Since the trunk is not in itself a rigid body (RB), the accuracy of the AdMos sensors were further tested on an RB. Four sensors were taped in a line to an RB which was also equipped with 4 reflective markers in the same configuration as the ISB recommendations for the trunk segment, to simulate a rigid trunk. The RB was then manually rotated in a manner (speed and range) similar to what can be expected of the trunk during sit-skiing, while both the IMU and MC systems recorded at 200 and 100 Hz, respectively.

All data was analyzed in Matlab 2021b (Mathworks Inc., Natick, MA, USA) and RStudio v4.2.1 for comparison. The IMU data was resampled to 100 Hz, and both data sets were then filtered using a 4th order 8Hz low-pass Butterworth filter. The trunk segment was defined as per the ISB recommendations from the MC data (Wu et al., 2005). The segment angle was calculated from both the gyroscope data and acceleration data from the IMU using the *complementaryFilter* function in Matlab. Due to the nature of the DP movement, only the sagittal plane movements (flexion-extension) were assessed for this study. Both angles (from IMU and the MC) are presented as the absolute angle of the segment with respect to the vertical plane.

The individual DP cycles were identified based on the peak positive angular velocity (angle derivation in MC and gyroscope data in IMU). The data from each cycle was time-normalized to 100 data points. The maximal, minimal, and range of motion (ROM, calculated as the cycle minima subtracted from the cycle maxima) values for the trunk angle were extracted for each cycle from both datasets and analyzed with Bland-Altman plots using the critical t-value to calculate the 95% limits of agreement to compensate for the small sample size (with the difference quantified as the IMU measure minus the MC measure), root mean square error (RMSE) and mean absolute percentage error (MAPE).

RESULTS: The analysis showed stronger agreements between the AdMos IMUs and the MC system during the RB test compared to during sit-skiing (Table 1). Both the RMSE and MAPE were largest for the high speed-low incline trial (10km/h at 0.5% incline).

Table 1: RMSE and MAPE values from the RB test and the Sit-ski tests performed at different speeds and inclines.

Task	Statistic	Max	Min	ROM
RB	RMSE (°)	0.4	0.5	0.5
	MAPE (%)	1.5	1.3	1.0
Sit-ski (10 km/h, 0.5% inc.)	RMSE (°)	2.0	1.6	3.4
	MAPE (%)	14.3	5.6	8.0
Sit-ski (4 km/h, 5.0% inc.)	RMSE (°)	3.6	2.7	2.7
	MAPE (%)	16.2	12.6	7.7

The Bland-Altman limits of agreement were small for the RB test (max: 1.83°, min: 2.21°, ROM: 1.66°) and moderate for the sit-ski test (10 km/h: max: 10.65°, min: 12.25°, ROM: 6.97°, 4 km/h: max: 8.36°, min: 12.14°, ROM: 7.8°; Figure 1). Note that the Bland-Altman plots only are shown for the ROM data since the plots for the Max and Min data showed the same trends. However, the plots also showed that the sensors often provided a larger measurement than the MC system during the Sit-ski trials, as indicated by the positive mean difference between the systems (2.96° during the 10km/h. trial and 1.91° during the 4km/h. trial).

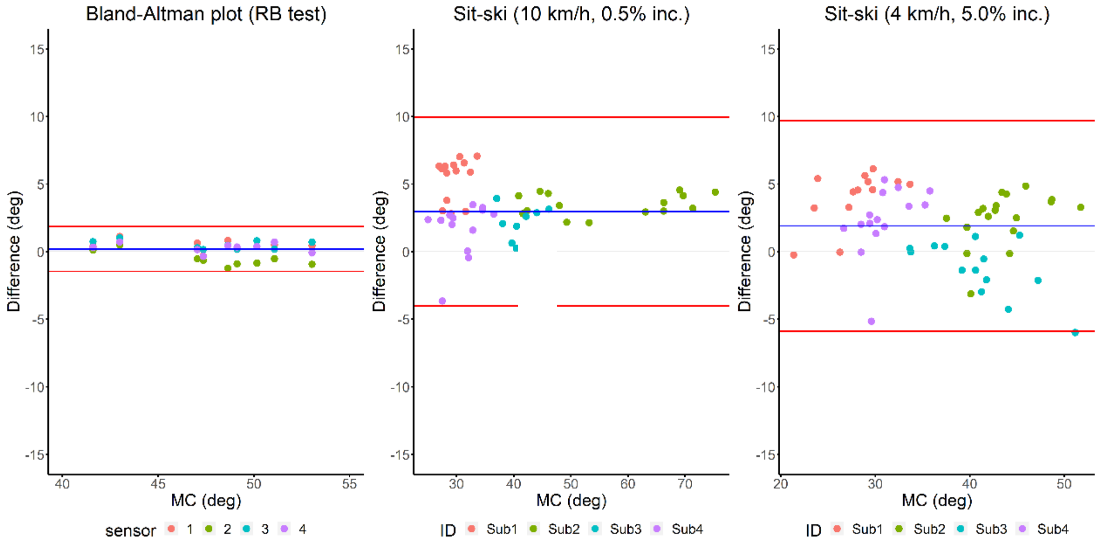

Figure 1: Bland-Altman plots of the ROM data from the RB-test and the two Sit-ski tests. The red lines indicate the 95% limits of agreement, and the blue line indicates the mean.

DISCUSSION: The Sit-ski tests showed that a single AdMos IMU sensor mounted on the upper back can provide a moderate estimation of the sagittal plane trunk motions during sit-skiing. The agreement with the MC system was between 1.6 and 3.6° (5.6 and 16.2%) which can be considered a ‘good-to-acceptable’ agreement (McGinley et al., 2009), and is similar to what has been reported for IMUs during other tasks (e.g., Robert-Lachaine et al., 2017; Saber-Sheikh et al., 2010). It can also be highlighted that the reliability within-subject is quite high (Figure 1). Further, the IMU appears to be able to distinguish ROM between individuals and the agreement remains similar despite different ROM (e.g., Sub2 at 10 km/hr.). Since the amount of trunk involvement available to a sit-ski athlete has a considerable effect on their ability to produce high speeds (Rosso et al., 2018), quantifying the amount of trunk function is an important part of the classification. Our data shows that IMUs can provide an estimation of the athletes’ sagittal plane trunk motions during competition, and thereby provide an empirical tool for the classification process. This is beneficial since a current challenge to classifiers is athletes who underperform during the tests to exaggerate their disability and receive a more favorable classification (Tweedy et al., 2014), so an empirical estimation of trunk function can reduce the risk of wrongly classifying the athlete.

Establishing a well-functioning classification process constitutes a central aspect in Para-sports since it aims at ensuring fairness of competition without compromising performance (Sherrill, 1999) and it continues to develop with new research. Since the classification is performed at the competition venues, it is beneficial that the assessment methods require little equipment while maintaining precision, as well as inter-, and intra-tester reliability (Tweedy et al., 2014). The agreement shown in this study endorse the use of IMU sensors since they are portable and provide an accurate and reliable measurement of the sagittal plane trunk motion during sit-skiing.

Further, while it is likely that an athlete with more trunk function utilizes larger trunk motions, one must acknowledge that factors other than disability may affect the ROM, such as technique, equipment, and strapping. Therefore, basing classification solely on the measured trunk motion during skiing may not be appropriate. Nevertheless, this study has shown that equipping sit-ski athletes with even a single IMU on their upper back during skiing can provide an acceptable estimation of the amount of trunk motion the athletes use. It may, therefore, be used as another tool in the classification process and assist classifiers in correctly assign the athletes to the appropriate class for a fairer competition.

The weaker agreements during the Sit-ski trials compared to the RB test shows that the trunk is not an RB and that this affects the accuracy of the sensor measurements. However, since the ISB trunk model also assumes that the trunk (between C7 and T8) is an RB (Wu et al., 2005), it is likely that also the MC measure contains this error to some degree. Further, during sit-skiing, the arms and shoulder girdle is substantially active, which may affect the measurements of an IMU fixed to the upper back more than it does the measurements of the ISB trunk model.

CONCLUSION: This study has shown that a single AdMos IMU sensor placed on the upper back can provide a reasonable estimation of the amount of sagittal plane trunk movement during sit-skiing. This is encouraging since it shows that IMUs may be a valuable tool for classifiers and help contribute towards a fair competition in Para Nordic skiing.

REFERENCES

Bjerkefors, A., Tinmark, F., Nilsson, J., & Arndt, A. (2013). Seated double-poling ergometer performance of individuals with spinal cord injury - a new ergometer concept for standardized upper body exercise. *International Journal of Sports Medicine*, *34*(2), 176-182. https://doi.org/10.1055/s-0032-1311653

Brice, S. M., Hurley, M., & Phillips, E. J. (2018). Use of inertial measurement units for measuring torso and pelvis orientation, and shoulder-pelvis separation angle in the discus throw. *International Journal of Sports Science & Coaching*, *13*(6), 985-992. https://doi.org/10.1177/1747954118778664

Guo, L., & Xiong, S. (2017). Accuracy of Base of Support Using an Inertial Sensor Based Motion Capture System. *Sensors (Basel)*, *17*(9), 2091. https://doi.org/10.3390/s17092091

Hegge, A. M., Bucher, E., Ettema, G., Faude, O., Holmberg, H. C., & Sandbakk, O. (2016). Gender differences in power production, energetic capacity and efficiency of elite cross-country skiers during whole-body, upper-body, and arm poling. *European Journal of Applied Physiology*, *116*(2), 291-300. https://doi.org/10.1007/s00421-015-3281-y

Lebel, K., Boissy, P., Nguyen, H., & Duval, C. (2017). Inertial measurement systems for segments and joints kinematics assessment: towards an understanding of the variations in sensors accuracy. *Biomedical Engineering Online*, *16*(1), 56, Article 56. https://doi.org/10.1186/s12938-017-0347-6

McGinley, J. L., Baker, R., Wolfe, R., & Morris, M. E. (2009). The reliability of three-dimensional kinematic gait measurements: a systematic review. *Gait and Posture*, *29*(3), 360-369. https://doi.org/10.1016/j.gaitpost.2008.09.003

Ohlsson, M. L., & Laaksonen, M. S. (2017). Erratum to: Sitting position affects performance in cross-country sit-skiing. *European Journal of Applied Physiology*, *117*(10), 2123-2124. https://doi.org/10.1007/s00421-017-3694-x

Robert-Lachaine, X., Mecheri, H., Larue, C., & Plamondon, A. (2017). Validation of inertial measurement units with an optoelectronic system for whole-body motion analysis. *Medical and Biological Engineering and Computing*, *55*(4), 609-619. https://doi.org/10.1007/s11517-016-1537-2

Rosso, V., Gastaldi, L., Rapp, W., Lindinger, S., Vanlandewijck, Y., Ayramo, S., & Linnamo, V. (2018). Balance Perturbations as a Measurement Tool for Trunk Impairment in Cross-Country Sit Skiing. *Adapted Physical Activity Quarterly*, 1-16. https://doi.org/10.1123/apaq.2017-0161

Saber-Sheikh, K., Bryant, E. C., Glazzard, C., Hamel, A., & Lee, R. Y. (2010). Feasibility of using inertial sensors to assess human movement. *Manual Therapy*, *15*(1), 122-125. https://doi.org/10.1016/j.math.2009.05.009

Sherrill, C. (1999). Disability sport and classification theory: A new era. *Adapted Physical Activity Quarterly*, *16*(3), 206-215. https://doi.org/DOI10.1123/apaq.16.3.206

Tweedy, S. M., Beckman, E. M., & Connick, M. J. (2014). Paralympic classification: conceptual basis, current methods, and research update. *PM and R*, *6*(8 Suppl), S11-17. https://doi.org/10.1016/j.pmrj.2014.04.013

Wu, G., van der Helm, F. C., Veeger, H. E., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., Buchholz, B., & International Society of, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion--Part II: shoulder, elbow, wrist and hand. *Journal of Biomechanics*, *38*(5), 981-992. https://doi.org/10.1016/j.jbiomech.2004.05.042

ACKNOWLEDGEMENTS: We would like to thank the participants who made this study possible.