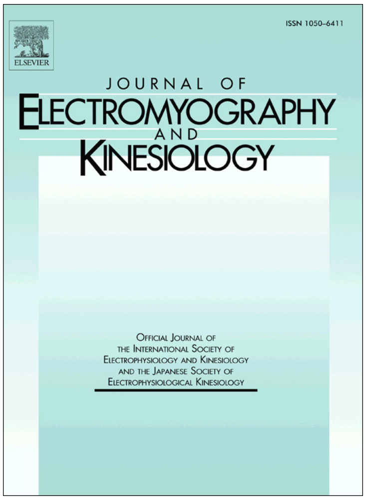
Accepted Manuscript



Concurrent validity and reliability of a novel wireless inertial measurement system to assess trunk movement

C.M. Bauer, F.M. Rast, M.J. Ernst, J. Kool, S. Oetiker, S.M. Rissanen, J.H. Suni, M. Kankaanpää

PII: S1050-6411(15)00115-7
DOI: http://dx.doi.org/10.1016/j.jelekin.2015.06.001
Reference: JJEK 1862

To appear in: *Journal of Electromyography and Kinesiology*

Received Date: 18 November 2014
Revised Date: 3 June 2015
Accepted Date: 4 June 2015

Please cite this article as: C.M. Bauer, F.M. Rast, M.J. Ernst, J. Kool, S. Oetiker, S.M. Rissanen, J.H. Suni, M. Kankaanpää, Concurrent validity and reliability of a novel wireless inertial measurement system to assess trunk movement, *Journal of Electromyography and Kinesiology* (2015), doi: http://dx.doi.org/10.1016/j.jelekin.2015.06.001

Concurrent validity and reliability of a novel wireless inertial measurement system to assess trunk movement.

*Bauer CM[12], Rast FM[2], Ernst MJ[2], Kool J[2], Oetiker S[2], Rissanen SM[3], Suni JH[4], Kankaanpää M[15]

*Corresponding author

Institution

1: Zurich University of Applied Sciences, Department of Health, Institute of Physiotherapy

2: University of Tampere, School of Medicine

3: University of Eastern Finland, Department of Applied Physics

4: UKK Institute for Health Promotion Research, Tampere, Finland

5: Tampere University Hospital, Department of Physical and Rehabilitation Medicine

Address

1: Technikumstrasse 71, 8400 Winterthur, Switzerland

2: Kalevantie 4, FI-33014 University of Tampere, Finland

3: University of Eastern Finland, P.O. Box 1627, 70211 Kuopio, Finland

4: Kaupinpuistonkatu 1, 33500 Tampere, Finland

5: Tampere University Hospital, P.O. Box 2000, 33521 Tampere, Finland

Telephone

1: +41 58 934 71 71

2&5: +358 3 355 111

3: +358 40 3552370

4: +358 3 282 9111

E mail

1: christoph.bauer@zhaw.ch

2&5: markku.kankaanpaa@pshp.fi

3: saara.rissanen@uef.fi

4: jaana.h.suni@uta.fi

Corresponding author

Christoph Bauer

Zurich University of Applied Sciences,

Departement of Health, Institute of Physiotherapy

Technikumstrasse 71

8400 Winterthur

Switzerland

Tel: +41 58 934 71 71

Fax. +41 58 935 71 71

christoph.bauer@zhaw.ch

Introduction

Movement dysfunctions in patients suffering from diseases such as low back pain (LBP), stroke and Parkinson’s disease can be clinically assessed by measuring their trunk range of motion (ROM) and their reaction to specific movement control tasks (Laird et.al., 2014), (Verheyden et.al., 2007), (Cole et.al., 2010). Specifically, these assessments are comprised of 1) ROM (Laird et.al., 2014), 2) movement control impairment (MCI) (Sahrmann, 2002, Luomajoki et a., 2007), 3) repetitive movement (RM) tests (Dideriksen et.al., 2014), and 4) tests for proprioception deficits such as reposition error tests (RE) (Rausch Osthoff et.al., 2015).

Optoelectronic measurement systems are accepted as gold-standards for non-invasive analysis of trunk movement within research settings (Cuesta-Vargas et.al., 2010, McGinley et.al., 2009). However they are not applicable in daily clinical practice due to their high cost, required installation space, specific marker placement and subsequent data capture, analysis and processing. These factors limit the analysis to some standard procedures, which cannot be extended to clinics (Wong and Wong, 2009). Alternative objective, valid, and reliable measurement systems are needed to allow clinicians to assess and monitor individual patient changes and compare between different population groups.

To overcome these limitations, new wireless movement analysis systems using body-worn sensors have recently been developed (e.g. Valedo® from Hocoma AG, ViMove from dorsaVi, or Reablo® from Corehab). These clinical systems comprise of multiple small light weight inertial measurement units (IMU) which measure the angular tilt and velocity of body segments with respect to magnetic fields and gravity (Roetenberg et.al., 2007). By combining the output of multiple IMU’s and post processing algorithms into an IMU-system it is possible to estimate joint angles in a non-invasive way.

Using concurrent validation, the output of an IMU system can be correlated to the gold-standard, whilst simultaneously measuring with both systems (Streiner and Norman 2008). Recent research examined concurrent validity of a wired IMU system and found a high correlation to the gold-standard (Wong and Wong, 2009, Wong et.al., 2007). However correlation studies between two systems should provide both a measure of random error, or precision, as well as accuracy of the devices in their units of measurement (e.g. degrees). (de Vet et.al., 2006). In a systematic review of the literature, Cuestas-Vargas and colleagues found that IMU systems can be concurrent to optoelectronic analysis of trunk measurements, but the degree of concurrent-validity is specific to the IMU system and anatomical site (Cuestas-Vargas et.al., 2010).

Reliable measures of trunk movement and control are needed to monitor individual changes over time and to compare between different individuals. Reliability concerns the degree to which repeated measures provide similar results (de Vet et.al., 2006). Reliability is affected by interrater, intrasession, and intersession variability (Corriveau et.al., 2000). Interrater variability is unlikely to be a concern for measurements with an IMU system, except for sensor placement. Variability of sensor placement can be minimised by using a standardised protocol (Ernst et.al., 2013). Intra- and intersession variability depend on biological variability, hence they are test specific. Reliable tests can be identified by estimating the magnitude of intra- and intersession variability. Furthermore, recommendations can be made for the number of trials needed to be averaged from one or more sessions in order to improve reliability (Santos et.al., 2008).

This study assesses concurrent validity of a novel wireless IMU system, by using an optoelectronic system as a gold standard. Second, it investigates the reliability of commonly used trunk movement and control tests, when measured with a wireless IMU system.

2. Methods

This study was divided into two sub-studies: A concurrent validity study (study V) and a reliability study (study R).

2.1 Participants

Twenty-two and twenty-four asymptomatic participants volunteered for studies V and R respectively. The participant's characteristics are presented in table 1. Detailed exclusion criteria for both studies are described elsewhere (Schelldorfer et.al., 2015). For study R, the sample size was calculated according to Walter et al (Walter et.al., 1998). Twenty participants and five trials allow reliability estimations of 0.95 with a type I error of 0.05 and a type II error of 0.20. The studies were approved by the local ethics commission and participants provided their informed consent.

2.2 Marker and sensor placement

Four IMUs were placed on the right thigh (THI), over the sacrum (S2), and at the level of L1 (L1), and T1 (T1), as described elsewhere (Ernst et.al., 2013, Schelldorfer et.al., 2015). The IMUs were mounted on a plastic frame and attached to the skin with hydrogel tape (KCI

Medical GmbH 8153 Rümlang, CH). Reflective markers were placed above and below every IMU with a third marker attached to the stiletto on the plastic frame. Thus it was possible to build virtual segments corresponding to the IMU plane, and to compare the two systems (Figure 1). The IMU and optoelectronic systems were synchronized using digital signals generated from a Labjack U3® data acquisition device (Labjack Corporation, USA).

2.3 Measurement systems and data processing

Trunk movements were measured by the IMU system in both studies and additionally with an optoelectronic motion capture system (VICON, Oxford UK) in study V. In study V, a fourth-order zero-phase low-pass Butterworth filter (6 Hz cut-off frequency) was used to filter the raw data of both systems. In study R, an eighth-order zero-phase low-pass Butterworth filter (6 Hz cut-off frequency) was used since we analysed acceleration and jerk, which are noisy measures and require smoothing to obtain interpretable estimates.

2.3.1 Optoelectronic System

The optoelectronic system consisted of twelve infrared cameras. Data was sampled at 200Hz and processed using VICON Nexus® software. The coordinate system of each segment, defined by three reflective markers, was aligned to the coordinate system of the IMU. The difference signal between two segments was calculated and transformed into tilt/twist angles according to Crawford and colleagues (Crawford et.al., 1999). We adopted the following sign convention: flexion, lateral flexion toward the right, and axial rotation toward the left were assigned positive values; movements in the opposite directions were assigned negative values. We termed the angle between the L1 and T1 segment “Thoracic Spine”, the angle between S2 and L1 “Lumbar Spine,” and the angle between thigh and S2 “Hip angle”.

2.3.2 Inertial measurement units

The Valedo® system (Hocoma AG) is a professional medical system used for low back pain therapy. The Valedo IMU’s contain a tri-axillar gyroscope, magnetometer, and accelerometer, as well as wireless antenna and signal processing unit. The specifications of the IMU’s indicate they are able to record ±0.1° over a range of 360° around all axes (Valedo® User Manual, Hocoma AG). IMU sensor data was transmitted to a recording computer with a 200 Hz sampling frequency. Custom data acquisition and synchronisation software (Valedo® Research) was provided by Hocoma AG. The raw IMU sensor data was transformed into quaternions according to Madgwick and colleagues (Madgwick et.al., 2010). The angular difference between two IMU's placed above the body segments was calculated and transformed into tilt/twist angles. A complete description of the data processing from raw data to tilt/twist angles is documented in supplementary File 1.

2.4 Procedures

2.4.1 Study V

Participants attended one measurement session and performed four ROM tests in randomized order, as described in Table 2. They were tutored by a video showing the correct movement. Additionally, they were instructed to move as far as possible at their preferred speed. Each test was performed three times.

2.4.2 Study R

Participants attended two identical measurement sessions, separated by a 1 week period. Both measurement sessions took place at the same time of day. All participants performed 14 tests, which were grouped into four categories according to their purposes: (1) ROM, (2) MCI, (3) RM and (4) RE. Test (1) measures the flexibility of the participant's spine within their comfort zone. Test (2) evaluates the participant's ability to control and differentiate movement between two body segments and to stabilize their spine. The former parameter was analysed by calculating the ratio of the ROM of the respective body segments, while the later was investigated using the ROM of the respective segment. Furthermore, the root mean squared jerk (RMSJ), as described by Slaboda et al. (Slaboda et.al., 2005), was calculated as indication of movement control. Test (3) measured the variability of angular displacement and acceleration during repeated movements. Variability was examined by calculating percentage of recurrence (%REC) and determinism (%DET) using recurrence quantification analysis (RQA) (Webber and Zbilut, 1994). Test (4) evaluates the participant's proprioceptive deficits within the spine, analysed using constant error (CE) (Rausch Osthoff et.al., 2015).

Participants performed four ROM, six MCI, two RM, and two RE tests as described in table 2. Each test was performed seven times, except for those in four point kneeling (4pk) which was reduced to 5 repetitions to minimise loading through their wrists. The order of the tests was randomized between participants but not between days.

2.5 Statistical Analysis

2.5.1 Study V

The coefficient of determination (r^2), a measure of precision, and root mean squared error (RMSE), a measure of accuracy, were used to test the concurrent validity of the IMU system:

$$r^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y})^2} \qquad RMSE = \sqrt{\frac{\sum_i (y_i - x_i)^2}{n}}$$

Where x and y are the two time based movement signals, and $\hat{y}_i$ being the predicted value obtained by linear regression. The values of r^2 ranged from 0 to 1. A high value of r^2 implies that angles measured by IMUs and the optoelectronic system have the same characteristic. RMSE is the measure of the average difference between the two signals. Systematic differences between the systems were analysed using the Wilcoxon rank sum-test with p set at <0.05.

2.5.2 Study R

The generalizability theory (Brennan, 2001) with the design $p \times t \times d$ ($participants \times trials \times days$) was used as a framework to estimate reliability of trunk movement measures, based on the linear model

$$X_{ptd} = \mu + v_p + v_t + v_d + v_{pt} + v_{pd} + v_{td} + v_{ptd}$$

with μ representing the global mean and v any one of the seven components.

The index of dependability Φ was calculated as:

$$\Phi = \frac{\sigma^2{}_p}{\sigma^2{}_p + \frac{\sigma^2{}_t}{n_t} + \frac{\sigma^2{}_d}{n_d} + \frac{\sigma^2{}_{pt}}{n_t} + \frac{\sigma^2{}_{pd}}{n_d} + \frac{\sigma^2{}_{td}}{n_t n_d} + \frac{\sigma^2{}_{ptd}}{n_t n_d}}$$

with σ being the variance, and n the number of the corresponding component (with n_t, n_p, and n_d being the number of trials, participants, and days, respectively). Φ was interpreted as: <0.25 very low, 0.26 – 0.49 – low, 0.50 – 0.69 – moderate, 0.70 – 0.89 – high, and >0.90 – very high reliability (Carter et.al., 2005). Φ≥0.70 was interpreted as sufficient to compare between different individuals. Subsequently, Φ coefficients were calculated for alternative measurement strategies, where n_t was varied up to ten trials, and n_d varied across two days, which represent acceptable measurement strategies. Thereby, the number of required trials per day to achieve high reliability was evaluated.

The coefficient of variation (CV) (Hopkins, 2000) was calculated as

$$CV = \frac{\sigma_{diff}}{\sqrt{n_d} * \bar{x}} * 100$$

with $\bar{x}$ being the grand mean and σ_{diff} being the standard deviation of the differences between days and calculated from the mean of seven trials per day. The CV values were rated as follows: >10% not reliable, 6-10% adequately reliable and 5% highly reliable. CV's ≤ 10% were construed as sufficient to monitor changes over time (Suni et.al., 2014).

The diagnostic value of a variable was assessed by Φ whereas the ability to detect changes over time was evaluated by the CV.

Results

Study V

In general, trunk movements in the sagittal plane were overestimated by the IMU system compared to the optoelectronic system (angular values between 1.3°-6.5°). In contrast, frontal plane movements of the trunk were underestimated (angular values between 0.7-3.1°). Movements of the hip were measured almost equally with both systems. A summary of the results is presented in Table 3.

No significant systematic differences were found in the primary movement direction, except for sagittal and frontal plane movement of the thoracic spine (flexion and lateral flexion to the right).

The measurement systems showed acceptable agreement and small measurement errors in the primary movement direction. The r^2 coefficients ranged between 0.94-0.99, except for hip movement during the lateral flexion tests (0.85-0.87) and the RMSE ranged between 1.1-6.8°. Flexion of the lumbar spine and the hip, as well as lateral flexion of the thoracic and lumbar spine, revealed very high agreement with an r^2 coefficient of 0.99 and RMSE ranging between 1.8-6.1°. In the non-primary movement directions, r^2 coefficients were lower (0.36-0.87) while RMSE were similar (1.2-6.8°) compared to the primary movement direction (Supplementary File 2).

Study R

Table 4 summarizes the grand mean, Φ-coefficients, and the number of trials averaged from one or two measurement days which are needed to gain Φ≥0.70, and the CV for each variable. On average, ROM and RM tests needed a smaller number of trials to reach high reliability and had smaller CVs compared to MCI and RE tests.

Measured values from single trial tests of trunk ROM revealed high to very high reliability except for extension of the lumbar spine. All CVs were smaller than 10%. The MCI tests differed in their reliability with Φ-coefficients of a single measurement ranging from low to high, and CVs from 8-22%. The RM tests showed CVs smaller than 10%, with the “Picking up a Box” test being more reliable than the “Flexion and Extension” test. The RE tests showed a respectively low reliability for a single measurement with CVs greater than 10%.

Discussion

The main findings of the present study were that the use of a wireless IMU system is a valid alternative to measure trunk movements in the primary movement direction when compared to the golden standard (i.e. an optoelectronic system). Secondly, on average, the ROM and RM tests needed a smaller number of repeated trials to reach high reliability and had smaller CVs when compared to the MCI and RE tests.

4.1 Study V

The measured ROM falls well within the range of previously published results, although comparability is hampered by a large variety of measurement approaches, including measurement systems and participants selection (Laird et.al., 2014). Both our optoelectronic and IMU systems measured similar ROM, whilst sagittal plane movement was slightly overestimated, and frontal plane movement underestimated, by the IMU systems.

This study showed that trunk ROM in the primary movement direction can be accurately measured by using a wireless IMU system; however, the system appears less valid for assessing movements in non-primary directions. Although RMSE were similar in magnitude compared to the primary movement direction, they were higher relative to the total ROM. The agreement could be affected by the noise, and limited resolution of the IMU system, a nonlinear correlation between both systems, and constraints on mathematical calculations.

The present study improves upon previous work (Ha et.al., 2013, Wong and Wong, 2009) with a more detailed analysis of ROM measures which includes thoracic spine and hip ROM. Furthermore, the concurrent validity of the novel wireless IMU system compares well to other studies validating different IMU systems against a gold-standard (Dunne et.al., 2006, Ha et.al., 2013, Wong and Wong, 2008, Wong and Wong, 2009).

4.2 Study R

The index of dependability Φ of a single trial varied across different tests and variables, ranging from 0.19 to 0.90. The CV varied considerably as well, ranging from <1-37%. Reliability can be improved by increasing the number of trials/days and using the mean value. While, for some variables, averaging over days affected reliability more than averaging over trials on one day, this is not necessarily a practical solution, especially in clinical settings. If one attempts to increase the number of trials, care should be taken that a learning-effect or fatigue does not influence the participants' performance (Santos et.al., 2008).

4.2.1 Range of motion

Three out of the four lumbar ROM variables reached high reliability with a single trial on one day, whereas the extension ROM only had moderate reliability. Averaging two single trials over two days increased the reliability of ROM extension more than averaging several trials on one day, indicating that it is affected more by sources of variance between days rather than within one day. The decreased reliability of ROM extension could be explained by biological variability between days, the test-setup, or the slightly lower concurrent validity of the IMU system (Table 3).

The low CVs (3-9%) indicate high reliability for measuring changes in ROM over time. These results are in accordance with other studies reporting high reliability of ROM measures (Al Zoubi and Preuss, 2013). The measured ROM is almost identical to study V and within the range of previously published results (Laird et.al., 2014).

4.2.2 Movement Control Impairment

The MCI tests differed in their reliability. "Waiters Bow" and "Sitting Knee Extension" reached high reliability when averaging a maximum of six trials on one day, or two trials on two days. The magnitude of the between-day variance is also shown by the CV, ranging between 8-22%. Nonetheless, the mean ROM in "Sitting Knee Extension" was approaching zero, with about 25% of participants moving into extension, hampering the interpretation of the CV (22%) for this variable. "Pelvic Tilt", "Rocking Forwards", "Rocking Backwards," and "Prone Knee Bend" showed little to moderate reliability. The reliability might be affected by the complexity or the standardisation of the MCI tests or because segment movement ranges, duration, and speed were not controlled. Standardizing the MCI tests for one of these factors might decrease within-day and between-days variance.

Our results are somewhat contradictory in regard to previous research, where the reliability of MCI tests was reported as substantial based on a dichotomous variable (positive or negative indication) (Luomajoki et.al., 2007). Although a growing body of research investigates MCI of the trunk and hip (Luomajoki et.al., 2007, Saner et al. 2015), no normative values have been published aside from this study. Additionally, the different approaches to quantify MCI tests make it difficult to compare our results.

4.2.3 Repeated Movement tests

The “Picking Up a Box” test had high reliability by averaging a maximum of four trials on one measurement day, with low CVs (⩽3%). Our descriptive results for %DET of angular displacement are comparable with previous research (Dideriksen et.al., 2014), which did not report reliability of their measures.

The ”Flexion and Extension” test showed lower Φ-values, whilst the CVs were also small (≤6%). “Picking Up a Box” is predominantly performed by flexing the spine and hips, while the second test is based on flexion and extension. In this study, measures of extension were less reliable and had lower concurrent validity, which might explain the lower Φ values. Both tests were highly standardized, possibly explaining the small standard deviations of these variables.

4.2.4 Reposition Error

Reposition error, CE (Rausch Osthoff et.al., 2015), reached high reliability after averaging six trials on one day (4pk) or eight trials across two days (sitting). The CE can have positive and negative values and a score of zero implies a good performance. These characteristics result in an expected grand mean around zero and, therefore, huge CVs. Consequently, the CV should not be interpreted for these two variables. In such situations Φ gives a better indication of reliability. The magnitude of the measured RE is well within the range of previously published data on pain-free participants (Rausch Osthoff et.al., 2015). Data on reliability of RE measures is discouraging. Several studies report poor reliability of RE tests, use an inadequate numbers of trials, or do not report reliability of their measures (Rausch Osthoff et.al., 2015).

4.3 Limitations of this study

The IMU system is a valid tool when measuring flexion of the lumbar spine and hip, as well as lateral flexion of the thoracic and lumbar spine. On the other hand, measurements of thoracic spine flexion and hip lateral flexion should be viewed with caution. Some of the differences between the two systems can be characterized as errors in the optoelectronic system. These errors could be triggered by camera noise, limited sight of markers, or vibrations of the marker frame (Ehara et.al., 1997). Additionally both systems are affected by skin surface artefacts caused by contraction of the muscles or prominent spinal processes (Yang et.al., 2008).

The sample size was calculated for an Intraclass-Correlation-Coefficient model (Walter et.al., 1998). We assume this to be appropriate as both models share similarities while generalizability theory is regarded as an expansion of classical reliability theory (Brennan, 2001). RMSJ was calculated as a measure of movement control that has been shown to be reliable and discriminative between populations (Slaboda et.al., 2005). However, RMSJ is sensitive to movement duration, amplitude, and arrest (Hogan and Sternad, 2009). Other indices of movement control could be investigated in future studies. This study has focused on pain-free participants. Although reliability is affected by the heterogeneity of study populations (Lariviere et.al., 2013), the inclusion of pain-free participants was reasonable to evaluate the usability of an IMU system to measure trunk kinematics.

4.4 Suggestions for future research

The evaluated wireless IMU system is appropriate as a more affordable alternative to an optoelectronic system within the demonstrated boundaries regarding secondary movement directions. The IMU system's concurrent validity might be enhanced by investigating the technical validity of the IMU components and subsequently improving these components.

Future studies should address reliability on different populations and assess diagnostic value and the ability to detect changes of the presented measures over time in more detail.

Differences between populations and treatment effects of interventions aiming at improving movement control have to be investigated. Measures of RQA in repeated movement tests are highly dependent on the input parameters (Rissanen et.al., 2008, Webber and Zbilut, 1994). Other choices for input parameters, apart from the ones used in our study (Table 5), are possible, and optimal input parameters have to be investigated in future studies.

4.5. Clinical implications and recommendations

Clinicians commonly use range of motion and movement control tests of the trunk and hip to assist in identifying patterns of dysfunction and to monitor change (Laird et.al., 2014). This paper presents a measurement tool which enables the clinicians to do this objectively. To identify dysfunctions and changes in performance, high reliability is important. Based on our results, we recommend the use of four ROM tests, selected MCI tests (“Waiters Bow” and “Sitting Knee Extension”), RE in 4pk, and “Picking up a Box” for RM, using an adequate number of trials for each test (Table 4).

5. Conclusion

The usage of a wireless IMU system led to valid estimates of trunk movement in the primary movement directions. A number of tests to assess movement dysfunctions and their corresponding variables were identified as reliable and should be studied further for intersubject comparisons and monitoring changes after an intervention.

Acknowledgements

The Swiss Commission of Technical Innovation funded this study.). Saara Rissanen was supported by the Academy of Finland. We thank Dr. Melissa Lawrence for language editing. We thank Mrs Rausch-Osthoff, Hausherr, Aegerter and Mr Heimgartner for assisting with data-acquisition.

References

Al Zoubi FM, Preuss RA. Reliability of a measure of total lumbar spine range of motion in individuals with low back pain. J Appl Biomech 2013;29(6):670-7.

Brennan RL. Generalizability Theory. 2nd ed. New York: Springer; 2001.

Carter RE, Lubinsky J, Domholdt E. Rehabilitation Research: Principles and Applications. 4th ed. St.Louis: Elsevier Saunders; 2005

Cole MH, Silburn PA, Wood JM, Worringham, CJ, Kerr GK. Falls in Parkinson’s disease: kinematic evidence for impaired head and trunk control. Mov Disord 2010;35(14):2369-78

Corriveau H, Hébert R, Prince F, Raiche M. Intrasession reliability of the «center of pressure minus center of mass» variable for postural control in the healthy elderly. Arch Phys Med Rehabil 2000;81(1):45-8

Crawford NR, Yamaguchi GT, Dickman CA. A new technique for determining 3-D joint angles: the tilt/twist method. Clin Biomech 1999;14(3):153-65.

Cuesta-Vargas AI, Galàn-Mercant A, Williams JM. The use inertial sensors system for human motion analysis. Phys Ther Rev 2010;15(6):105-10

de Vet HC, Terwee CB, Knol DL, Bouter LM. When to use agreement versus reliability measures. J Clin Epidemiol 2006;59(10):1033-9.

Dideriksen JL, Gizzi L, Petzke F, Falla D. Deterministic accessory spinal movement in functional tasks characterizes individuals with low back pain. Clin Neurophysiol 2014;125(8):1663-8.

Dunne LE, Walsh P, Herman, S, Smyth B, Caulfield B. Wearable monitoring of seated spinal posture. IEEE Tran Biomed Circuits Syst 2008;2(2):97-105

Ehara Y, Fujimoto H, Miyazaki S, Mochimaru M, Tanaka S, Yamamoto S. Comparison of the performance of 3D camera systems II. Gait Posture 1997;5(3):251-5.

Ernst M, Rast F, Bauer C, Marcar V, Kool J. Determination of thoracic and lumbar spinal processes by their percentage position between C7 and the PSIS level. BMC Res Notes 2013;6:58.

Ha TH, Saber-Sheikh K, Moore AP, Jones MP. Measurement of lumbar spine range of movement and coupled motion using inertial sensors - a protocol validity study. Man Ther 2013;18(1):87-91.

Hocoma AG. Valedo®Motion User Manual. 2nded. Volketswil: Hocoma AG; 2011

Hogan N, Sternad D. Sensitivity of smoothness measures to movement duration, amplitude, and arrests. J Mot Behav 2009;41(6):529-34.

Hopkins WG. Measures of reliability in sports medicine and science. Sports Med 2000;30(1):1-15.

Laird RA, Gilbert J, Kent P, Keating JL. Comparing lumbo-pelvic kinematics in people with and without back pain: a systematic review and meta-analysis. BMC Musculoskelet Disord 2014; 15:229.

Lariviere C, Mecheri H, Shahvarpour A, Gagnon D, Shirazi-Adl A. Criterion validity and between-day reliability of an inertial-sensor-based trunk postural stability test during unstable sitting. J Electromyogr Kinesiol 2013;23(4):899-907.

Luomajoki H, Kool J, de Bruin ED, Airaksinen O. Reliability of movement control tests in the lumbar spine. BMC Musculoskelet Disord 2007;8:90.

Madgwick S, Vaidyanathan R, Harrison A. An Efficient Orientation Filter for IMU and MARG Sensor Arrays. Department of Mechanical Engineering, University of Bristol; 2010.

Marwan N. Wessel U, Meyerfeldt A, Schirdewan A, Kurths J. Recurrence plot based measures of complexity and its application to heart rate variability data. Physical Review E 2002;66:026702

Rausch Osthoff AK, Ernst MJ, Rast FM, Mauz D, Graf ES, Kool J, et al. Measuring Lumbar Reposition Accuracy in Patients With Unspecific Low Back Pain: Systematic Review and Meta-analysis. Spine 2015;40(2):E97-E111.

Rissanen SM, Kankaanpaa M, Meigal A, Tarvainen MP, Nuutinen J, Tarkka IM, et al. Surface EMG and acceleration signals in Parkinson's disease: feature extraction and cluster analysis. Med Biol Eng Comput 2008;46(9):849-58.

Sahrmann S. Diagnosis and Treatment of Movement Impairment Syndromes. St. Louis, Missouri 63146 USA: Mosby; 2002.

Saner J, Kool J, Sieben JM, Luomajoki H, Bastianen CHG, De Bie RA. A tailored exercise program versus general exercise for a subgroup of patients with low back pain and movement control impairment: A randomised controlled trial with one-year follow-up. Man Ther 2015;inpress.

Santos BR, Delisle A, Lariviere C, Plamondon A, Imbeau D. Reliability of centre of pressure summary measures of postural steadiness in healthy young adults. Gait Posture 2008;27(3):408-15.

Schelldorfer S, Ernst MJ, Rast FM, Bauer CM, Meichtry A, Kool J. Low back pain and postural control, effects of task difficulty on centre of pressure and spinal kinematics. Gait Posture 2015;41(1):112-8.

Slaboda JC, Boston JR, Rudy TE, Lieber SJ, Rasetshwane DM. The use of splines to calculate jerk for a lifting task involving chronic lower back pain patients. IEEE Trans Neureal Syst Rehabil Eng 2005;13(3):406-14.

Streiner DL, Norman GR. Health Measurement Scales: A practical guide to their development and use. 4thed. Oxford:OUP, 2008.

Suni J, Rinne M, Ruiz J. Retest Repeatability of Motor and Musculoskeletal Fitness Tests for Public Health Monitoring of Adult Populations. J Nov Physiother 2014;4:1.

Verheyden G, Nieuwboer A, Van de Winckel A, De Weerdt W. Clinical tools to measure trunk performance after stroke: a systematic review of the literature. Clin Rehabil 2007;21(5):387-94

Walter SD, Eliasziw M, Donner A. Sample size and optimal designs for reliability studies. Stat Med 1998;17(1):101-10.

Webber CL, Jr., Zbilut JP. Dynamical assessment of physiological systems and states using recurrence plot strategies. J Appl Physiol 1994;76(2):965-73.

Wong WY, Wong MS. Trunk posture monitoring with inertial sensors. Eur Spine J. 2008;17(5):743-53.

Wong WY, Wong MS. Measurement of Postural Change in Trunk Movements Using Three Sensor Modules. IEEE Trans Instru Measure 2009;58(8):2737-42.

Wong WY, Wong MS, Lo KH. Clinical applications of sensors for human posture and movement analysis: a review. Prosthet Orthot Int 2007;31(1):62-75.

Yang Z, Ma HT, Wang D, Lee R. Error analysis on spinal motion measurement using skin mounted sensors. Conf Proc IEEE Eng Med Biol Soc 2008;4740-3.

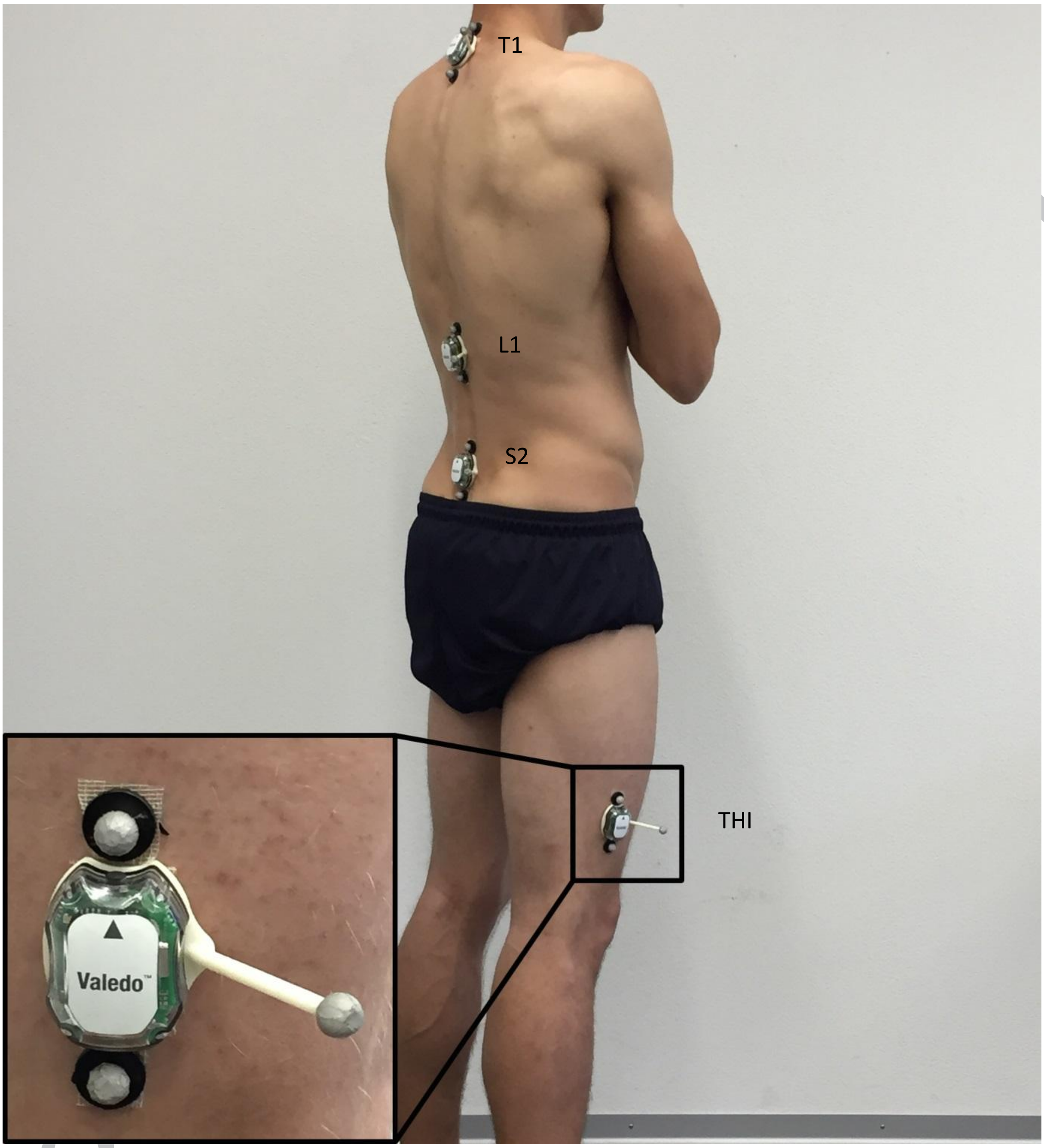


Fig 1.
Experimental setup: The THI, S2, L1, T1 IMU, and the reflective markers

Table 1

Participant's demographics (mean ± standard deviation)

Study V	All (n=22)	Women (n=11)	Men (n=11)
Age (years)	41.18 ± 11.14	38.27 ± 10.44	44.09 ± 11.53
Body mass index	22.99 ± 2.89	22.67 ± 3.02	23.32 ± 2.85
Study R	All (n=24)	Women (n=13)	Men (n=11)
Age (years)	38.04 ± 11.21	37.77 ± 10.12	38.44 ± 12.60
Body mass index	22.93 ± 2.69	22.58 ± 3.12	23.44 ± 1.85

n: number of participants

Table 2

Overview of the tests and variables for each test

Test	Starting Position	Movement	BS	Variable (unit)	Description of variable
ROM Tests					
ROM Flexion	Standing upright	Maximal flexion of the LS	LS	ROM_FLEX (°)	ROM LS
ROM Extension	Standing upright	Maximal extension of the LS	LS	ROM_EXT (°)	ROM LS
ROM Lateral Flexion Right	Standing upright	Maximal lateral flexion of the LS	LS	ROM_RIGHT (°)	ROM LS
ROM Lateral Flexion Left	Standing upright	Maximal lateral flexion of the LS	LS	ROM_LEFT (°)	ROM LS
MCI Tests (Luomajoki et al., 2007)					
Pelvic Tilt	Standing upright	Anterior pelvic tilt without moving the trunk or knees	LS TS	RATIO_PT RMSJ_PT_LS (°/s^3) (Slaboda et al., 2005) RMSJ_PT_TS (°/s^3)	ROM LS/ ROM TS Smoothness of movement
Waiters Bow	Standing upright	Hip flexion without moving the LS	LS Hip	RATIO_WB RMSJ_WB_LS (°/s^3) RMSJ_WB_Hip (°/s^3)	ROM LS/ ROM Hip Smoothness of movement Smoothness of movement
Sitting Knee Extension	Sitting upright Hips at 90°	Knee extension without moving the LS	LS	ROM_SKE (°) RMSJ_SKE_LS (°/s^3)	ROM LS Smoothness of movement
Rocking Backwards	4pk	Hip flexion and shoulder extension without moving the LS	LS Hip	RATIO_RB RMSJ_RB_LS (°/s^3) RMSJ_RB_Hip (°/s^3)	ROM LS/ ROM Hip Smoothness of movement Smoothness of movement
Rocking Forwards	4pk	Hip extension and shoulder flexion without moving the LS	LS Hip	RATIO_RF RMSJ_RF_LS (°/s^3) RMSJ_RF_Hip (°/s^3)	ROM LS/ ROM Hip Smoothness of movement Smoothness of movement
Prone Knee Bend	Lying prone	Knee flexion without moving the LS	LS	ROM_PKB (°) RMSJ_PKB_LS (°/s^3)	ROM LS Smoothness of movement
RM Tests (Dideriksen et al., 2014)					
Picking Up a Box	Standing upright	Lifting a box (5% body weight) five times in a row at 60bpm	LS	%REC_PU_AD, %DET_ PU_AD (%) %REC_ PU_AA, %DET_ PU_AA (%)	percentage of recurrence points within a recurrence plot (%REC) and percentage of recurrence points forming diagonal line structures in this plot (%DET)
Flexion and Extension	Sitting upright Hips at 60°	Repeated flexion and extension of the trunk, five times in a row at 80bpm	LS	%REC_ FE_AD, %DET_ FE_AD (%) %REC_ FE_AA, %DET_FE_AA (%)	

					(Webber and Zbilut, 1994, Marwan et al., 2002, Rissanen et al., 2008)
RE Tests (Rausch-Osthoff et al., 2014)					
Reposition Error Sitting	Sitting upright Hips at 60°	Flexion of the trunk and reproducing the starting position	LS	CE_SIT (°)	Angular difference between starting and final position
Reposition Error 4pk	4pk	Extension of the LS and reproducing the starting position	LS	CE_4PK (°)	Angular difference between starting and final position

4pk: four point kneeling; %DET: percentage of determinism; %REC: percentage of recurrence; AA= angular acceleration; AD: angular displacement; bpm: beats per minute; BS: Body segment; CE: constant error; EXT: Extension; FE: Flexion and Extension; FLEX: Flexion; LS: lumbar spine; MCI: Movement control impairment; PKB: prone knee bend; PT: Pelvic Tilt; PU: Picking Up a Box; RB: rocking backwards ;RE: Reposition Error; RF: rocking forwards; RM: repetitive movement; RMSJ: root mean squared jerk; ROM: range of motion; SKE sitting knee extension; SIT: sitting; TS: Thoracic Spine; WB: waiters bow

Table 3

Study V Results for Trunk Range of Motion Measures, primary movement direction

	ROM Thoracic Spine, °				**ROM Lumbar Spine, °**				**ROM Hip, °**			
	IMU System, ° Mean ± SD	Optoelectronic System, ° Mean ± SD	r^2 Mean ± SD	RMSE, ° Mean ± SD	IMU System, ° Mean ± SD	Optoelectronic System, ° Mean ± SD	r^2 Mean ± SD	RMSE, ° Mean ± SD	IMU System. ° Mean ± SD	Optoelectronic System, ° Mean ± SD	r^2 Mean ± SD	RMSE, ° Mean ± SD
ROM Flexion	36.2 ± 11.9 *	29.7 ± 10.9 *	0.95 ±0.04	5.8 ± 2.0	53.3 ± 10.9	50.71 ± 9.5	0.99 ±0.01	4.1 ±1.8	77.4 ± 15.3	77.1 ± 14.2	0.99± 0.01	6.1 ± 2.7
ROM Extension	22.2 ± 9.9	18.9 ± 9.9	0.94 ±0.09	5.9 ± 3.3	16.6 ± 10.5	15.3 ± 8.4	0.97 ±0.05	4.4 ± 2.2	13.7 ± 5.8	14.8 ± 5.8	0.94±0.09	5.6 ± 4.1
ROM Lateral Flexion Right	31.9 ± 5.1 *	35.0 ± 6.1 *	0.99 ±0.01	2.8 ± 1.4	22.8 ± 5.1	23.7 ± 5.1	0.99 ±0.01	1.8 ± .0	7.3 ± 4.3	7.3 ± 4.9	0.87±0.21	1.1 ± .7
ROM Lateral Flexion Left	32.6 ± 9.2	34.7 ± 10.3	0.99 ±0.03	2.6 ± 2.0	22.2 ± 5.7	22.9 ± 6.5	0.99±0.01	1.9 ± 1.3	6.8 ± 3.0	6.9 ± 3.4	0.85±0.20	1.1 ± .7

IMU: inertial measurement units; r^2: R-squared; RMSE: root mean squared error; ROM: range of motion; SD: standard deviation; * indicates a significant systematic difference between the two systems

Table 4

Study R Results of Trunk Movement Measures: Reliability of a single measure, number of trials averaged on one or two days needed to achieve high reliability and coefficient of variation

Test	**Variable; Unit**	**Mean ± SD**	**Φ one trial**	**Number trials Φ >0.7 One day**	**Number trials Φ>0.7 two days**	**CV (%)**
ROM Tests						
ROM Flexion	ROM_FLEX (°)	53.6 9.6	0.80	1	1	3
ROM Extension	ROM_EXT (°)	-17.5 ± 7.9	0.63	>10	1	9
ROM Lateral Flexion Right	ROM_RIGHT (°)	-20.7 ± 7.3	0.90	1	1	3
ROM Lateral Flexion Left	ROM_LEFT (°)	21.2 ± 6.8	0.90	1	1	3
MCI Tests						
Pelvic Tilt	RATIO_PT	.16 ± 0.1	0.27	>10	7	16
	RMSJ_PT_TS (°/s^3)	4.2 ± 3.1	0.27	>10	>10	15
	RMSJ_PT_LS (°/s^3)	72.5 ± 49.1	0.35	>10	>10	20
Waiters Bow	RATIO_WB	.54 ± .44	0.77	1	1	10
	RMSJ_WB_LS (°/s^3)	48.8 ± 31.7	0.68	2	1	8
	RMSJ_WB_Hip (°/s^3)	61.7 ± 35.5	0.51	6	2	11
Sitting Knee Extension	ROM_SKE (°)	1.9 ± 2.8	0.68	2	1	22
	RMSJ_SKE_LS (°/s^3)	17.5 ± 8.9	0.62	3	1	8
Rocking Backwards	RATIO_RB	.71 ± .43	0.38	>10	>10	18
	RMSJ_RB_LS (°/s^3)	29.3 ± 12.9	0.44	8	2	10
	RMSJ_RB_Hip (°/s^3)	28.4 ± 9.9	0.39	8	3	8
Rocking Forward	RATIO_RF	1.52 ± 1.16	0.19	>10	>10	11
	RMSJ_RF_LS (°/s^3)	35.2 ± 20.9	0.73	1	1	9
	RMSJ_RF_Hip (°/s^3)	31.1 ± 12.4	0.31	>10	9	12
Prone Knee Bend	ROM_PKB (°)	-4.0 ± 2.7	0.44	>10	3	14
	RMSJ_PKB_LS (°/s^3)	24.9 ± 13.5	0.45	>10	8	14
RM Tests						
Picking Up a Box	%REC_PU_AD (°)	0.15 ± 0.01	0.68	3	2	2
	%DET_PU_AD (°)	0.97 ± 0.01	0.51	3	2	<1
	%REC_PU_AA (°/s^2)	0.13 ± 0.01	0.63	4	2	3
	%DET_PU_AA (°/s^2)	0.74 ± 0.04	0.65	3	2	2
Flexion and Extension	%REC_FE_AD (°)	0.13 ± 0.01	0.29	>10	>10	4
	%DET_FE_AD (°)	0.97 ± 0.01	0.64	5	3	<1
	%REC_FE_AA (°/s^2)	0.08 ± 0.01	0.24	>10	>10	4
	%DET_FE_AA(°/s^2)	0.66 ± 0.07	0.60	6	3	6
RE Tests						

Reposition Error Sitting	CE_SIT (°)	-.94 ± 1.4	0.19	>10	8	37
Reposition Error 4pk	CE_4PK (°)	1.6 ± 1.8	0.30	6	4	22

4pk: four point kneeling; Φ: index of dependability; %DET: percentage of determinism; %REC: percentage of recurrence; AA= angular acceleration; AD: angular displacement; CE: constant error; CV: Coefficient of variation; EXT: Extension; FE: Flexion and Extension; FLEX: Flexion; LS: lumbar spine; MCI: Movement control impairment; PKB: prone knee bend; PT: Pelvic Tilt; PU: Picking Up a Box; RB: rocking backwards ;RE: Reposition Error; RF: rocking forwards; RM: repetitive movement; RMSJ: root mean squared jerk; ROM: range of motion; SKE sitting knee extension; SIT: sitting; SD: Standard deviation; TS: Thoracic Spine; WB: waiters bow

Table 5

Input parameters used in recurrence quantification analysis

Test	Delay	Embedding Dimension
Picking Up a Box		
Angular Displacement	15	4
Angular Acceleration	13	4
Flexion and Extension		
Angular Displacement	19	4
Angular Acceleration	14	4

Christoph Bauer received his BSc in physiotherapy from the Hoogeschool of Amsterdam, the Netherlands, and his MSc in physiotherapy from Philips-University Marburg, Germany. He is currently a PhD student at Tampere University, School of Medicine, Finland and vice head of research at the institute of Physiotherapy, Zurich University of Applied Sciences.

Fabian Rast received his MSc in Movement Science from the Federal Technical University Switzerland, Zurich, Switzerland. He is currently researcher at the movement laboratory of the Institute of Physiotherapy, Zurich University of Applied Sciences.

Sarah Oetiker received her MSc in Movement Science from the Federal Technical University Switzerland, Zurich, Switzerland. She is currently researcher at the movement laboratory of the Institute of Physiotherapy, Zurich University of Applied Sciences.

Markus Ernst received his MSc in Physiotherapy from Maastricht University, the Netherlands. He is currently researcher at the Institute of Physiotherapy, Zurich University of Applied Sciences.

Jan Kool received his MSc and PhD in Physiotherapy from Maastricht University, the Netherlands. He was head of research and development at the institute of physiotherapy, Zurich University of Applied Sciences from 2006 until 2013. He is currently researcher and physiotherapist at the Clinic Valens, Switzerland.

Saara Rissanen received her MSc and PhD in Physics from University of Eastern Finland, Finland. She is currently researcher at the Department of Applied Physics, University of Eastern Finland, Finland.

Jaana Suni received her MSc and PhD in Exercise Therapy from University of Jyväskylä, Finland. She is a senior researcher at the UKK Institute, Tampere Finland.

Markku Kankaanpää received his MD and PhD in Medicine from University of Eastern Finland, Finland. He is currently associated professor of rehabilitation medicine at University of Tampere, Finland.

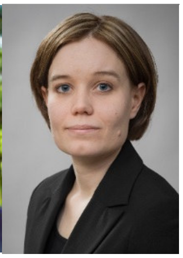

C Bauer


F Rast


S Oetiker


M Ernst


J Kool


S Rissanen


J Suni


M Kankaanpää

Abstract: Introduction
Assessment of movement dysfunctions commonly comprises trunk range of motion (ROM), movement or control impairment (MCI), repetitive movements (RM), and reposition error (RE). Inertial measurement unit (IMU)-systems could be used to quantify these movement dysfunctions in clinical settings. The aim of this study was to evaluate a novel IMU-system when assessing movement dysfunctions in terms of concurrent validity and reliability.

Methods
The concurrent validity of the IMU-system was tested against an optoelectronic system with 22 participants. The reliability of 14 movement dysfunction tests were analysed using generalizabilitytheory and coefficient of variation, measuring 24 participants in seven trials on two days.

Results
The IMU-system provided valid estimates of trunk movement in the primary movement direction when compared to the optoelectronic system. Reliability varied across tests and variables. On average, ROM and RM were more reliable, compared to MCI and RE tests.

Discussion
When compared to the optoelectronic system, the IMU-system is valid for estimates of trunk movement in the primary movement direction. Four ROM, two MCI, one RM, and one RE test were identified as reliable and should be studied further for inter-subject comparisons and monitoring changes after an intervention.

Keywords: Generalizability-Theory; Movement Disorders; Reproducibility of Results; Biomechanical Phenomena