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

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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 al., 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 (TH1), 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:

$$r^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \bar{y})^2}$$

$$\text{RMSE} = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n}}$$

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 × trials × days) was used as a framework to estimate reliability of trunk movement measures, based on the linear model

$$X_{p,t,a} = \mu + \nu_p + \nu_t + \nu_a + \nu_{pt} + \nu_{pa} + \nu_{pta}$$

with $\mu$ representing the global mean and $\nu$ any one of the seven components.

The index of dependability $\Phi$ was calculated as:

$$\Phi = \frac{\sqrt{\sum_{i=1}^{k} \frac{\sigma_i^2}{n_i}}}{\sqrt{\frac{\sigma_p^2}{n_p} + \frac{\sigma_t^2}{n_t} + \frac{\sigma_a^2}{n_a} + \frac{\sigma_{pt}^2}{n_{pt}} + \frac{\sigma_{pa}^2}{n_{pa}} + \frac{\sigma_{pta}^2}{n_{pta}}}}$$

with $\sigma$ being the variance, and $n$ the number of the corresponding component (with $n_p$, $n_t$, and $n_a$ being the number of trials, participants, and days, respectively). $\Phi$ 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). $\Phi \geq 0.70$ was interpreted as sufficient to compare between different individuals. Subsequently, $\Phi$ coefficients were calculated for alternative measurement strategies, where $n_t$ was varied up to ten trials, and $n_a$ 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
with \( \bar{\mathbf{x}} \) being the grand mean and \( \sigma_{\text{diff}} \) 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 \( \Phi \) 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, \( \Phi \)-coefficients, and the number of trials averaged from one or two measurement days which are needed to gain \( \Phi \geq 0.70 \), 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 $\Phi$ 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.

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Fig 1.
Experimental setup: The THI, S2, L1, T1 IMU, and the reflective markers
Table 1
Participant’s demographics (mean ± standard deviation)

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

n: number of participants
### Table 2
Overview of the tests and variables for each test

<table>
<thead>
<tr>
<th>Test</th>
<th>Starting Position</th>
<th>Movement</th>
<th>BS</th>
<th>Variable (unit)</th>
<th>Description of variable</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ROM Tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM Flexion</td>
<td>Standing upright</td>
<td>Maximal flexion of the LS</td>
<td>LS</td>
<td>ROM_FLEX (*)</td>
<td>ROM LS</td>
</tr>
<tr>
<td>ROM Extension</td>
<td>Standing upright</td>
<td>Maximal extension of the LS</td>
<td>LS</td>
<td>ROM_EXT (*)</td>
<td>ROM LS</td>
</tr>
<tr>
<td>ROM Lateral Flexion Right</td>
<td>Standing upright</td>
<td>Maximal lateral flexion of the LS</td>
<td>LS</td>
<td>ROM_RIGHT (*)</td>
<td>ROM LS</td>
</tr>
<tr>
<td>ROM Lateral Flexion Left</td>
<td>Standing upright</td>
<td>Maximal lateral flexion of the LS</td>
<td>LS</td>
<td>ROM_LEFT (*)</td>
<td>ROM LS</td>
</tr>
<tr>
<td><strong>MCI Tests (Luomajoki et al., 2007)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvic Tilt</td>
<td>Standing upright</td>
<td>Anterior pelvic tilt without moving the trunk or knees</td>
<td>LS</td>
<td>RATIO_PT</td>
<td>ROM LS/ ROM TS</td>
</tr>
<tr>
<td>Waiters Bow</td>
<td>Standing upright</td>
<td>Hip flexion without moving the LS</td>
<td>LS</td>
<td>RATIO_WB</td>
<td>ROM LS/ ROM Hip</td>
</tr>
<tr>
<td>Sitting Knee Extension</td>
<td>Sitting upright</td>
<td>Knee extension without moving the LS</td>
<td>LS</td>
<td>ROM_SKE (*)</td>
<td>Smoothness of movement</td>
</tr>
<tr>
<td>Rocking Backwards</td>
<td>4pk</td>
<td>Hip flexion and shoulder extension without moving the LS</td>
<td>LS</td>
<td>RATIO_RB</td>
<td>Smoothness of movement</td>
</tr>
<tr>
<td>Rocking Forwards</td>
<td>4pk</td>
<td>Hip extension and shoulder flexion without moving the LS</td>
<td>LS</td>
<td>RATIO_RF</td>
<td>Smoothness of movement</td>
</tr>
<tr>
<td>Prone Knee Bend</td>
<td>Lying prone</td>
<td>Knee flexion without moving the LS</td>
<td>LS</td>
<td>ROM_PKB (*)</td>
<td>Smoothness of movement</td>
</tr>
<tr>
<td><strong>RM Tests (Dideriksen et al., 2014)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Picking Up a Box</td>
<td>Standing upright</td>
<td>Lifting a box (5% body weight) five times in a row at 60bpm</td>
<td>LS</td>
<td>%REC PU_AD, %DET PU_AD (%)</td>
<td>percentage of recurrence points within a recurrence plot (%REC) and percentage of recurrence points forming diagonal line structures in this plot (%DET)</td>
</tr>
<tr>
<td>Flexion and Extension</td>
<td>Sitting upright</td>
<td>Repeated flexion and extension of the trunk, five times in a row at 80bpm</td>
<td>LS</td>
<td>%REC_FE_AD, %DET_FE_AD (%)</td>
<td>percentage of recurrence points forming diagonal line structures in this plot (%DET)</td>
</tr>
<tr>
<td>RE Tests (Rausch-Osthoff et al., 2014)</td>
<td></td>
<td></td>
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<tr>
<td>Reposition Error Sitting</td>
<td>Sitting upright</td>
<td>Flexion of the trunk and reproducing the starting position</td>
<td>LS CE_SIT (*)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reposition Error 4pk</td>
<td>4pk</td>
<td>Extension of the LS and reproducing the starting position</td>
<td>LS CE_4PK (*)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th></th>
<th>ROM Thoracic Spine, °</th>
<th>ROM Lumbar Spine, °</th>
<th>ROM Hip, °</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IMU System, ° Mean ± SD</td>
<td>Optoelectronic System, ° Mean ± SD</td>
<td>r² Mean ± SD</td>
</tr>
<tr>
<td><strong>ROM Flexion</strong></td>
<td>36.2 ± 11.9 * ±0.04</td>
<td>29.7 ± 10.9 * 2.0</td>
<td>0.95</td>
</tr>
<tr>
<td><strong>ROM Extension</strong></td>
<td>22.2 ± 9.9 ±0.09</td>
<td>18.9 ± 9.9 3.3</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>ROM Lateral Flexion Right</strong></td>
<td>31.9 ± 5.1 * ±0.01</td>
<td>35.0 ± 6.1 * 1.4</td>
<td>0.99</td>
</tr>
<tr>
<td><strong>ROM Lateral Flexion Left</strong></td>
<td>32.6 ± 9.2 ±0.03</td>
<td>34.7 ± 10.3 2.6</td>
<td>0.99</td>
</tr>
</tbody>
</table>

IMU: inertial measurement units; r²: 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

<table>
<thead>
<tr>
<th>Test</th>
<th>Variable; Unit</th>
<th>Mean ± SD</th>
<th>Φ one trial</th>
<th>Number trials Φ &gt;0.7</th>
<th>Number trials Φ &gt;0.7</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>One day</td>
<td>two days</td>
<td>One day</td>
<td>two days</td>
<td></td>
</tr>
<tr>
<td><strong>ROM Tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROM Flexion</td>
<td>ROM_FLEX (*)</td>
<td>53.6 ± 9.6</td>
<td>0.80</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>ROM Extension</td>
<td>ROM_EXT (*)</td>
<td>-17.5 ± 7.9</td>
<td>0.63</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>9</td>
</tr>
<tr>
<td>ROM Lateral Flexion Right</td>
<td>ROM_RIGHT (*)</td>
<td>-20.7 ± 7.3</td>
<td>0.90</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>ROM Lateral Flexion Left</td>
<td>ROM_LEFT (*)</td>
<td>21.2 ± 6.8</td>
<td>0.90</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td><strong>MCI Tests</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvic Tilt</td>
<td>RATIO_PT</td>
<td>.16 ± 0.1</td>
<td>0.27</td>
<td>&gt;10</td>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>RMSI_PT_TS (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>4.2 ± 3.1</td>
<td>0.27</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>RMSI_PT_LS (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>72.5 ± 49.1</td>
<td>0.35</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>20</td>
</tr>
<tr>
<td>Waiters Bow</td>
<td>RATIO_WB</td>
<td>.54 ± .44</td>
<td>0.77</td>
<td>1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>RMSI_WB_LS (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>48.8 ± 31.7</td>
<td>0.68</td>
<td>2</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>RMSI_WB_Hip (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>61.7 ± 35.5</td>
<td>0.51</td>
<td>6</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Sitting Knee Extension</td>
<td>ROM_SKE (*)</td>
<td>1.9 ± 2.8</td>
<td>0.68</td>
<td>2</td>
<td>1</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>RMSI_SKE_LS (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>17.5 ± 8.9</td>
<td>0.62</td>
<td>3</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Rocking Backwards</td>
<td>RATIO_RB</td>
<td>.71 ± .43</td>
<td>0.38</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>RMSI_RB_LS (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>29.3 ± 12.9</td>
<td>0.44</td>
<td>8</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>RMSI_RB_Hip (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>28.4 ± 9.9</td>
<td>0.39</td>
<td>8</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Rocking Forward</td>
<td>RATIO_RF</td>
<td>1.52 ± 1.16</td>
<td>0.19</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>RMSI_RF_LS (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>35.2 ± 20.9</td>
<td>0.73</td>
<td>1</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>RMSI_RF_Hip (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>31.1 ± 12.4</td>
<td>0.31</td>
<td>&gt;10</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Prone Knee Bend</td>
<td>ROM_PKB (*)</td>
<td>-4.0 ± 2.7</td>
<td>0.44</td>
<td>&gt;10</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>RMSJ_PKB_LS (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>24.9 ± 13.5</td>
<td>0.45</td>
<td>&gt;10</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td><strong>RM Tests</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Picking Up a Box</td>
<td>%REC_PU_AD (*)</td>
<td>0.15 ± 0.01</td>
<td>0.68</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>%DET_PU_AD (*)</td>
<td>0.97 ± 0.01</td>
<td>0.51</td>
<td>3</td>
<td>2</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Flexion and Extension</td>
<td>%REC_FE_AD (*)</td>
<td>0.13 ± 0.01</td>
<td>0.29</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>%DET_FE_AD (*)</td>
<td>0.97 ± 0.01</td>
<td>0.64</td>
<td>5</td>
<td>3</td>
<td>&lt;1</td>
</tr>
<tr>
<td></td>
<td>%REC_FE_AA (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>0.08 ± 0.01</td>
<td>0.24</td>
<td>&gt;10</td>
<td>&gt;10</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>%DET_FE_AA (°/s&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>0.66 ± 0.07</td>
<td>0.60</td>
<td>6</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td><strong>RE Tests</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Test</th>
<th>Delay</th>
<th>Embedding Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Picking Up a Box</td>
<td></td>
<td></td>
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<tr>
<td>Angular Displacement</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>Angular Acceleration</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>Flexion and Extension</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular Displacement</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>Angular Acceleration</td>
<td>14</td>
<td>4</td>
</tr>
</tbody>
</table>
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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 generalizability theory 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