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Validity and reliability of pressure-measurement insoles for vertical ground reaction force assessment in field situations

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ABSTRACT

This study aimed to test the validity and reliability of pressure-measurement insoles (medilogic® insoles) when measuring vertical ground reaction forces in field situations. Various weights were applied to and removed from the insoles in static mechanical tests. The force values measured simultaneously by the insoles and force plates were compared for 15 subjects simulating work activities. Reliability testing during the static mechanical tests yielded an average interclass correlation coefficient of 0.998. Static loads led to a creeping pattern of the output force signal. An individual load response could be observed for each insole. The average root mean square error between the insoles and force plates ranged from 6.6% to 17.7% in standing, walking, lifting and catching trials and was 142.3% in kneeling trials. The results show that the use of insoles may be an acceptable method for measuring vertical ground reaction forces in field studies, except for kneeling positions.

1. Introduction

Mechanical exposures at work (e.g., lifting and manual materials handling) are associated with the occurrence of musculoskeletal disorders (Yassi and Lockhart, 2013). These exposures are common and occur in, for instance, construction work and the health care sector. The majority of previous studies have been based on subjective reports of mechanical occupational exposure (manual material handling). Recent studies indicate that previously established risk factors, such as forward-bending work posture, may be considered untenable by studies based on objective measurements of work exposures (Villumsen et al., 2015) and that subjective reports may be inadequate for assessing physical activity (Dyrstad et al., 2014). Hence, it is crucial to obtain valid and reliable measurements of exposure to learn which specific aspects of such mechanical work exposure contribute to musculoskeletal disorders.

Mechanical exposures are characterized by the type of work executed, including the posture, movements, and exerted forces involved (Westgaard and Winkel, 1996; van der Beek and Frings-Dresen, 1998). Although valid and reliable methods for measuring posture and movements with accelerometers are available, there are not a sufficient number of objective assessments for forces exerted during tasks involving lifting in a field setting.

The forces exerted by workers during lifting and carrying can be estimated by measuring ground reaction forces using force plates, shoes instrumented with force sensors, or pressure measurement insoles. Force plates measure ground reaction forces with a high level of accuracy in the horizontal and vertical directions (3D), but their use is limited in laboratory conditions. Shoes instrumented with force sensors may suitable for the measurement of forces in 3D at work sites. To our knowledge, the XSENS ForceShoe (XSENS North America Inc., Culver City, CA, USA) is the only commercially available system. However, due to the shoe's 3.2 cm sole height and total weight of 1.1 kg, this shoe may hinder normal working tasks and is inadequate when safety shoes are compulsory. Several researchers have used self-constructed force measurement insoles (Faivre et al., 2004; Liedtke et al., 2007; Saito et al., 2011; Razak et al., 2012); however, this approach is time consuming and requires a validation process. Therefore, commercial pressure measurement insoles may be a more practical choice (Forner Cordero

Abbreviations: 3D, 3-dimensional; ICC, intraclass correlation coefficient; MaxE, maximum error; RMSE, root mean square error.

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et al., 2004; Forner-Cordero et al., 2006; Fong et al., 2008). Commercial systems discussed in the literature or found on the market include Footscan pressure insoles (RSscan International, Paal, Belgium), Pedar® insoles (Novel GmbH, Munich, Germany), F-Scan pressure measurement insoles (Tekscan Inc., Boston, USA), and medilogic® insoles (T&T medilogic Medizintechnik GmbH, Schönefeld, Germany).

The validity, reliability or applicability differs depending on the system. Footscan pressure insoles showed high test-retest reliability but low validity during walking trials (Low and Dixon, 2010). Measured force values with Pedar® insoles increased up to 17% during 3-h walking trials (Arndt, 2003), by 43.2% during a static loading experiment and by 19% during an 8-h repeated load application (Hurkmans et al., 2006). Up to 30% lower peak forces during walking trials were observed for F-Scan insoles (Nicolopoulos et al., 2000). El Kati observed a rapid decrease in sensitivity in running trials and a frequent need for calibration with the F-Scan insoles (El Kati et al., 2010). The poor durability of the F-Scan insoles (El Kati et al., 2010; Woodburn and Helliwell, 1996) renders this system inefficient for measurements at the workplace. In general, the differences in validity and reliability compared to force platforms may be due their construction. Pedar® insoles are based on capacitive sensors, whereas the three other pressure measurement insoles mentioned above are based on resistive sensors.

Medilogic® insoles were chosen because they were considered applicable for field measurements at the worksite due to their durability and because they allow for 8-h collection of the raw data for each sensor of the insoles on a data logger (with SD-card). This study aimed to examine the validity and reliability of these pressure-measurement insoles for use in simulated work tasks relevant for construction and health care work.

2. Material and methods

2.1. Study design

To evaluate the applicability of pressure-measurement insoles for the field measurement of vertical ground reaction forces, medilogic® insoles were tested for validity and reliability via mechanical static tests during loading and unloading of the insoles as well as via tests in which participants simulated field situations with insoles placed in their shoes. During the simulated field situations, force plate measurements were carried out simultaneously for comparison.

2.2. Study population

Insoles were tested in simulated field situations using 15 healthy subjects (6 female, 9 male) with a mean age, weight, and height of 31.2 years (range: 21–50 years), 69.4 kg (range: 50–98 kg), and 169.3 cm (range: 157–193 cm), respectively. All of the participants were free of musculoskeletal problems for at least two months prior to participation. The participants were informed of the general aim of the study, the order and content of the measurements, and possible risks. All of the subjects signed an informed consent form prior to participation. The experiment was approved by the Regional Committee for Medical and Health Research Ethics (Ref. no.: 2013/2160 A) and conducted in accordance with the Helsinki Declaration.

2.3. Procedure for mechanical static tests

Mechanical static tests were performed by loading the insoles with weights ranging from 0 to 80 kg in steps of 5, 10 or 20 kg. Starting from an unloaded state, additional weight was placed on the insoles every 25 s until 80 kg was reached. The same procedure was then followed in the reverse order, reducing the weight every 25 s until the insole was unloaded (Fig. 1B). The procedure was repeated five times for each insole. Pressure values were recorded with a sampling frequency of 30 Hz. During the loading procedure, the insoles were placed in a self-constructed tripod between two triangular aluminum plates that were connected by a guide rail at each corner (Fig. 1A). Two 1-cm-thick rubber mats with sizes matched to the insoles were used between the insoles and the aluminum plates to prevent damage to the insoles and obtain a uniform pressure distribution.

2.4. Procedure for the simulation of field situations

Starting from an upright standing position with each foot placed on a separate force platform, the participants performed the following six working tasks: *Standing*: The participant was asked to stand as still as possible and look straight ahead for 1 min. *Walking*: Each participant walked on a straight 5-m track that had two separate force platforms in it. Both the left and right feet naturally stepped on one of the force platforms along the path. *Lifting an object*: A weight was placed on the floor in front of the force plates, with its position marked with tape. The participant lifted the object when given the command to lift it and then stood still in an upright position for 5 s. After 5 s, the weight was placed back on the floor, and the participant re-assumed the upright position. Trials were performed without weights and with weights of 10 and 15 kg. *Kneeling*: From a standing position (position 1), the participant knelt with their trunk in a vertical position with feet on the platforms and knees on the floor next to the force platforms (position 2). Next, the subjects put both hands in front of their knees and moved their trunk into a horizontal position (position 3). Finally, they moved back to the kneeling position (position 2) and rose back to the upright position (position 1). Instructions for new positions were given every 5 s. *Catching an object*: In the standing position, the subject had to catch a thrown 5-kg ball with both hands. *Free walking on even ground*: The participant walked freely in the laboratory without stepping on the force platforms while carrying a weight object. Trials were performed for 30 s each, and the weights carried ranged from 0 to 30 kg in steps of 5 kg.

All of the trials were repeated three times in a randomized order. One jump was performed at the beginning of each measurement to synchronize the times of both systems through the peak force at landing, except in the free walking trials, where no synchronization was needed. During the tasks, the pressures under the participant's feet were measured with insoles placed in their shoes on top of the regular insoles. The sampling frequency was 30 Hz. Simultaneous ground reaction forces were measured bilaterally by the force platforms (AMTI LG6-4-1, size: 120×60 cm^2, Watertown, MA, USA) with a sample frequency of 6000 Hz. Various sizes of the insoles were tested bilaterally in three different subjects (EUR: 37/38, 39/40, 41/42, 43/44, and 45/46). The size of the insoles was chosen based on the participant's shoe size. Prior to testing, each participant had to perform a standard calibration procedure for the insoles. To account for pre-existing pressure due to the tightness of the shoe, the participant was asked to sit in a chair with their feet lifted off the ground for 10 s. They then stood upright for 10 s on the left foot followed by 10 s on the right foot to normalize the measured pressure of each insole to their body weight.

2.5. Data analysis

Time synchronization and calculations of forces, correlations, and root mean square errors (RMSEs) were performed using Matlab