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Validation of a commercial inertial sensor system for spatiotemporal gait measurements in children

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ABSTRACT

Although inertial sensor systems are becoming a popular tool for gait analysis in both healthy and pathological adult populations, there are currently no data on the validity of these systems for use with children. The purpose of this study was to validate spatiotemporal data from a commercial inertial sensor system (MobilityLab) in typically-developing children. Data from 10 children (5 males; 3.0–8.3 years, mean = 5.1) were collected simultaneously from MobilityLab and 3D motion capture during gait at self-selected and fast walking speeds. Spatiotemporal parameters were compared between the two methods using a Bland-Altman method. The results indicate that, while the temporal gait measurements were similar between the two systems, MobilityLab demonstrated a consistent bias with respect to measurement of the spatial data (stride length). This error is likely due to differences in relative leg length and gait characteristics in children compared to the MobilityLab adult reference population used to develop the stride length algorithm. A regression-based equation was developed based on the current data to correct the MobilityLab stride length output. The correction was based on leg length, stride time, and shank range-of-motion, each of which were independently associated with stride length. Once the correction was applied, all of the spatiotemporal parameters evaluated showed good agreement. The results of this study indicate that MobilityLab is a valid tool for gait analysis in typically-developing children. Further research is needed to determine the efficacy of this system for use in children suffering from pathologies that impact gait mechanics.

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1. Introduction

The past several years have seen increased use of inertial sensors to analyze movement in laboratory, clinic, and daily living environments [1]. By utilizing accelerometers, gyroscopes, or magnetometers (or a combination of these), inertial sensors can provide a wealth of data regarding the characteristics of global and segment-specific movement during a variety of tasks. Additionally, the sensors and recording equipment are relatively compact, portable, and low cost compared to traditional laboratory-based equipment (such as multi-camera 3D motion capture or instrumented mats), and can be used to collect human movement data in environments and contexts where the use of traditional equipment is not possible. Inertial sensor technology that can be used in both laboratory and clinical environments has the potential to be a widely applicable method for researchers and clinicians to evaluate gait in a variety of healthy and clinical populations.

One widely-used inertial sensor system is the MobilityLab system (APDM, Portland, OR). This system utilizes six inertial sensors, each containing tri-axial accelerometers, gyroscopes, and magnetometers providing a comprehensive evaluation of the spatiotemporal characteristics of motion during a variety of pre-programmed testing protocols [2–4]. Data collected from these sensors is transmitted wirelessly to a software program, which uses algorithms based on aggregated reference data that have been validated against both 3D motion capture and force plate data to calculate the spatiotemporal characteristics (such as stride time, stride length, and velocity of each stride) of movement [3–5]. The

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system is also capable of discriminating between different movements associated with various mobility tests such as the sit-to-stand and turning phases of the timed-up-and-go test [6], and has been used in the evaluation of gait and mobility in clinical populations including persons with Parkinson's disease and multiple sclerosis [7,8].

While previous research has indicated that inertial sensor systems such as MobilityLab are a valid and reliable method of analyzing movement in adults [9], there has yet to be any research on the validity of their use in children. Since achieving functional gait and maximizing ambulatory independence are two of the most important functional outcomes for children suffering from musculoskeletal and neurological pathologies [10], it is crucial for clinicians to be able to analyze gait in children to recognize and attempt to correct any impairments and sub-optimal movement patterns that may be limiting functional capacity. Compared to traditional measurement tools used for gait analysis, inertial sensors offer several distinct benefits when working with children. The sensors are much easier to don and doff than reflective marker sets and use Velcro straps rather than adhesives, reducing the chances of skin irritation and/or discomfort during removal. Additionally, while most methods of gait analysis restrict movement to a given space or require the child to contact a target with their foot, the sensors allow the child to walk using their normal movement pattern with no environmental constraints.

While some research exists evaluating the use of inertial sensors as a tool for gait analysis in children with cerebral palsy [11–13], there are currently no data evaluating the validity of inertial sensor systems relative to 3D motion capture (the gold standard of gait analysis). Direct measurements of kinematic parameters like linear acceleration and angular velocity from inertial systems are fairly accurate; however indirect measures such as spatiotemporal parameters often rely on algorithms with assumptions and reference values based on adult data. It is unclear if these approaches will result in accurate data when applied to children.

The objective of this study is to validate the use of the MobilityLab inertial sensor system to obtain spatiotemporal parameters of gait in typically-developing children by comparing the level of agreement between data from the sensors and those obtained via 3D motion capture. We hypothesize that temporal data based on event detection will be accurate but estimations of spatial data may be influenced by adult-data assumptions inherent to the MobilityLab algorithms.

2. Methods

Ten typically-developing children (five males) participated in the study (mean age 5.1 yrs, range 3.0 yrs–8.3 yrs). Participants were eligible for the study if they were between the ages of three and 10, free of any neurological disorders or lower limb musculoskeletal injuries, and were full term ($\geq$37 weeks gestational age) at birth. The study was approved by the institutional Research Ethics Board and informed consent was obtained from the children's guardians. In addition to obtaining informed consent from each child's guardian, all of the participants gave verbal assent prior to their involvement in the study.

Data were collected from each child as they walked in a straight line along a 7 m long walkway. Each child performed six to eight walking trials with approximately half the trials at a self-selected velocity. In the other half of the trials, the child was instructed to walk faster without running. The result was a range of walking velocities, with an overall mean velocity of 1.07 m/s, an average minimum of 0.83 m/s (SD 0.18 m/s) and an average maximum 1.51 m/s (SD 0.24 m/s). Encouragement was provided as needed to maintain the child's attention and engagement but the child walked without any hands-on assistance.

Height was obtained to the nearest 0.1 cm using a stadiometer (mean 106.8 cm, range 93.5 cm–118.0 cm). Leg length (mean 42.7%, range 37.5 to 47.8%) was estimated as a percentage of total height from the motion capture data and was defined as the vertical length from the greater trochanter to the ankle (averaged across both legs) during standing.

The MobilityLab system (version 1.0.0.201503302135) was used to collect the inertial-based spatiotemporal and kinematic data. Each child wore a total of six inertial sensors positioned on the dorsal side of both wrists, on the sternum close to the clavicular notch, on the lower back in correspondence to L4/L5, and on the frontal side of the shanks close to the malleoli. Data were collected wirelessly at a sampling rate of 128 Hz using MobilityLab's iWalk module, which is designed for straight line walking of indeterminate length.

Simultaneously, reference kinematic data were collected at 100 Hz using an 8 camera 3D motion capture system (Vicon Nexus, Centennial, CO). Reflective tracking markers (14 mm diameter) were fixed to the areas of the greater trochanter, lateral femoral condyle, lateral malleoli, heel and toe of both legs. Additionally, three tracking markers (9 mm diameter) were fixed to the inertial sensor on the sternum with two markers in line with a sensor axis and the third defining a cardinal plane in sensor coordinate system. Foot contact and lift off were detected from the motion capture data using a manually-tuned automated foot velocity threshold algorithm [14,15] and were used to calculate temporal data. Spatial data (i.e. stride length) were calculated using the heel position data.

Inertial and motion capture data were synchronized during post-processing using custom software (Matlab R2006b, Mathworks, Natick, MA). Three dimensional acceleration of the sternum inertial sensor was calculated using motion capture data and transformed into the sensor coordinate system. These data were then time-matched to within 0.01 s of the corresponding raw sensor accelerometer data using a custom semi-automatic correlation method which used cross-correlation to provide an initial guess and then manual adjustment to find the final synchronization point.

Data from six strides from each of the right and left legs were randomly chosen from each participant resulting in a total of 120 strides used for analysis. Four main spatiotemporal variables were compared between the systems; stride time (StrT), stance time (StnT), stride length (StrL) and stride velocity (StrV). StrT was defined as the time from heel strike on one foot to the next heel strike of the same foot. StrV was calculated on a stride-by-stride basis as the ratio of StrL and StrT. StnT was assessed in addition to StrT as both heel strike and toe off identification are included in StnT calculations. According to the MobilityLab manufacturer [16], the procedures used to generate temporal and stride length data from the inertial sensors are based on published algorithms [3,5].

For this study, the video-based motion capture system was assumed to be the gold standard. Data were compared between the two methods using the Bland-Altman method [17,18]. The Bland-Altman method allows for comparisons between two different measurement systems to assess agreement when measuring the same set of data. The method provides an estimate of the bias between the systems and a measure of agreement known as limits of agreement (LoA). Since the magnitude of the some of the variables appeared to influence the bias, bias values and LoA were tested for significant non-zero slopes [18] and, when this was found, were fitted using linear regression [18]. Additionally, mean differences and root mean square (RMS) differences between the two systems were calculated. All statistics were calculated using SPSS (Version 23, IBM Corp, Armonk, NY).

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