Medical Engineering and Physics 38 (2016) 225–231

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Validity of an inertial measurement unit to assess pelvic orientation angles during gait, sit–stand transfers and step-up transfers: Comparison with an optoelectronic motion capture system*

S.A.A.N. Bolink [a,*], H. Naisas [a], R. Senden [a], H. Essers [b], I.C. Heyligers [a], K. Meijer [b], B. Grimm [a]

[a] AHORSE Foundation, Atrium Medical Centre, Department of Orthopaedics & Traumatology, Heerlen, The Netherlands
[b] Maastricht University, Department of Human Movement Science, Faculty of Health, Medicine and Life Sciences, Maastricht, The Netherlands

ARTICLE INFO

Article history:
Received 25 March 2015
Revised 18 November 2015
Accepted 29 November 2015

Keywords:
Inertial measurement unit
Optoelectronic motion capture system
Pelvic orientation angles
Gait
Sit-to-stand
Block step-up
Physical function
Performance-based test
Outcome assessment
Osteoarthritis
Arthroplasty

ABSTRACT

An inertial measurement unit (IMU) allows kinematic evaluation of human motion with fewer operational constraints than a gold standard optoelectronic motion capture (MOCAP) system. The study's aim was to compare IMU and MOCAP measurements of dynamic pelvic orientation angles during different activities of daily life (ADL): gait, sit-to-stand (STS) transfers and block step-up (BS) transfers. A single IMU was attached onto the lower back in seventeen healthy participants (8F/9 M, age 19–31 years; BMI < 25) and optical skin markers were attached onto anatomical pelvic landmarks for MOCAP measurements. Comparisons between IMU and MOCAP by Bland–Altman plots demonstrated that measurements were between 2SD of the absolute difference and Pearson's correlation coefficients were between 0.85 and 0.94. Frontal plane pelvic angle estimations achieved a RMSE in the range of [2.7°–4.5°] and sagittal plane measurements achieved a RMSE in the range of [2.7°–8.9°] which were both lowest in gait. Waveform peak detection times demonstrated ICCs between 0.96 and 1.00. These results are in accordance to other studies comparing IMU and MOCAP measurements with different applications and suggest that an IMU is a valid tool to measure dynamic pelvic angles during various activities of daily life which could be applied to monitor rehabilitation in a wide variety of musculoskeletal disorders.

1. Introduction

An optoelectronic motion capture (MOCAP) system is regarded as the gold standard to quantify human body kinematics in clinical studies [1,2]. MOCAP is however not feasible for routine clinical use because it is time consuming, expensive, requires a specially equipped laboratory with trained personnel and it is limited to a specific motion capture volume, constrained by space and equipment [3–5]. Consequently, many clinical studies evaluating physical performance use timed parameters, such as the six minute walk test (6MWT), timed up-and-go test (TUG) and stair climbing test (SCT), which have limited sensitivity and may not adequately discriminate between variations in subtle pathologies [6]. An inertial measurement unit (IMU) might open new perspective for these functional tests as it allows detailed spatiotemporal and kinematic measurements of human motion in a continuous modality [7,8]. An IMU is a commercially available, low-cost, small, lightweight and ambulant sensor, typically comprising a tri-axial accelerometer, tri-axial gyroscope, and tri-axial magnetometer. Through sensor fusion algorithms, the three-dimensional orientation can be estimated relative to a global coordinate system, based on the magnetic north and gravity which is referred to as Attitude and Heading Reference Systems (AHRS), traditionally expressed in Euler angles (yaw ψ, pitch θ, and roll ϕ) [3,9]. By attaching an IMU onto a body segment, the orientation of that body segment can be determined which allows kinematic evaluation of motion in realistic environments and conditions, with fewer operational constraints compared to MOCAP [3,10]. A systematic review of the literature by Cuesta-Vargas et al. [11] comparing IMU to gold standard optoelectronic MOCAP systems, demonstrated that an IMU can be applied to many body regions accurately and reliably but the degree of reliability is specific to the IMU system and anatomical site [11]. Most validation studies however attach the optical markers onto the IMU which means that only the measurement accuracy of the two systems is compared, but not the results of an IMU based motion analysis to an optoelectronic motion analysis [12]. Only a few studies have compared IMU with MOCAP by attaching the optical markers onto anatomical landmarks [12–15], remaining

* Correspondence to: Department of Orthopedics, Atrium Medical Center Heerlen, Henri Dunantstraat 5, 6419 PC Heerlen, the Netherlands. Tel.: +31 655341492; fax: +31 455766055.
E-mail address: stijn.bolink@mail.com, stijn009@hotmail.com (S.A.A.N. Bolink).

http://dx.doi.org/10.1016/j.medengphy.2015.11.009
1350-4533/

the variable inaccuracies due to relative motion between soft tissue and the underlying bony segments which are a potential source of measurement error [16]. Furthermore, whether the measurement error is acceptable and IMU data are considered reliable enough depends on the intended clinical application. Of interest in this paper is the routine clinical assessment of physical function in patients with hip or knee osteoarthritis (OA), for which a consensus derived set of functional tests enhanced with ambulatory motion analysis has been recommended in the literature [17]. Previous work described a method for ambulatory motion analysis of gait, sit-to-stand transfers and step-up transfers with a single inertial sensor positioned at the lower back in patients with knee OA [18] with sensitivity to postoperative changes following total knee arthroplasty [19]. This specific method has been adopted and reproduced by other researchers to assess functional outcome following total joint arthroplasty [20,21]. However, the validity of kinematic measurements from a single IMU positioned at the lower back during these activities has not yet been well determined.

The aim of this study was to compare kinematic measurements by an IMU attached on the lower back to a MOCAP system with optical markers placed on anatomical landmarks during gait, sit–stand transfers and step-up transfers, relevant for the assessment of physical function in patients with hip or knee OA [17,18].

2. Materials and methods

2.1. Equipment

Kinematic data were simultaneously obtained with an inertial measurement unit (IMU) and an optoelectronic motion capture (MOCAP) system. The IMU (size: 41 × 63 × 24 mm; weight: 39 g; MicroStrain® Inertia-Link®) comprises a tri-axial magnetometer, tri-axial gyroscope (±300°/s) and tri-axial accelerometer (±5 g) [22]. The IMU's output data quantities are calibrated for misalignment and the advertised technical specifications provided by the manufacturer indicate a gyro stability bias of ± 0.2°/s for movements at an angular velocity of ± 300°/s with static accuracy of ± 0.5° and dynamic accuracy of ± 2.0°. The IMU provides dynamic orientation angle estimation (yaw ψ, pitch θ, and roll ϕ) as separate output signals through inbuilt integration of the gyroscope signal by a microprocessor fusing the acceleration, angular rate and magnetic field vector measurements while performing fundamental data filtering to address drift error. The IMU was attached onto the skin using a double-sided adhesive tape and positioned at the lower back between both PSIS (posterior superior iliac spine) anatomical pelvic landmarks. Real-time data from the IMU were stored onto a computer via a wireless Bluetooth connection with a sampling frequency of 100 Hz. Data analysis was performed running analysis algorithms in MATLAB® (MathWorks®) version R2009a [18]. The MOCAP system was set-up with six VICON MX-3+ and two VICON MX-T20 cameras and one Kistler 9281A pressure plate. Emitted LED signals were reflected by skin markers with a diameter of 15 mm that were attached on the participants' anatomical pelvic landmarks according to the VICON's Plug In Gait Full Body Model [23,24]. The pressure plate was synchronized with the VICON cameras for heel strike detection during gait analysis and data were transmitted with a frequency of 200 Hz and analyzed with Nexus software.

2.2. Participants

Participants (n = 17; 8 females and 9 males; age range 19–31 years; mean age 25.8 years; BMI range 18.9–24.9 kg/m^2; mean BMI 21.6 kg/m^2) were randomly recruited from a medical university campus. Exclusion criteria were any neurological or musculoskeletal disorder, previous lower extremity surgery, recent musculoskeletal trauma and obesity (BMI > 25 kg/m^2).

2.3. Tasks

Three tasks resembling activities of daily life (ADL) were used: gait, sit-to-stand transfers (STS) and block step-up transfers (BS). BS was used as a surrogate for stair climbing as it was considered a more feasible task to perform in an outpatient clinical setting. The tasks were performed in a standardized order, at self-selected speed and were all repeated twice.

(1) Gait
Participants walked a 10 m distance at preferred speed. Across the finish line, one last step was allowed to avoid a significant slowdown aiming to reach the marked distance [25]. The exact distance covered (10 m + the last step) was measured to calculate IMU-based spatiotemporal gait parameters (i.e. speed, cadence, step time) obtained from the raw antero-posterior acceleration signal which serve as a reference [26,27]. IMU-based kinematic measurements represent the average of multiple gait cycles from the 10 m walked distance whereas MOCAP-based kinematic measurements are based on one gait cycle which was identified after heel strike on the pressure plate.

(2) STS
Participants performed STS transfers at preferred speed from a height adjustable chair in a standardized position: hips and knees were flexed in a 90° angle, both feet were parallel on the floor spread shoulder-width apart and arms were not allowed to swing while ascending [28].

(3) Block step-up (BS)
Participants performed BS transfers onto a 20 cm high wooden block at preferred speed. All participants stepped up with the right leg.

2.4. Statistical analysis

The output signals for dynamic pelvic angle estimations from IMU were analyzed with peak detection algorithms in MATLAB® and from MOCAP with Nexus software. The waveforms of both systems were plotted in MATLAB® to provide additional visual comparison. For each task, the range of motion (ROM) in the frontal plane and sagittal plane were calculated as these have been found the most relevant for functional assessment of gait, sit-to-stand transfers and step-up transfers with previously reported discriminative capacity between knee OA patients and healthy controls, in contrast to ROM in the transverse plane [18]. Agreements between ROM-measurements were compared by the plot of the difference between each paired measurement against the mean value of both (Bland Altman plots) and quantified by calculation of the root mean squared error (RMSE) and Pearson's correlation coefficient (r). To investigate waveform peak-to-peak displacement due to filtering and integration of the IMU's gyroscope signal, waveform peak detection times between IMU and MOCAP were compared with interclass correlation coefficients (ICCs; r) [29]. For gait, time between two maxima of consecutive gait cycles was compared and for STS and BS the time between two maxima of consecutive repetitions was compared.

3. Results

In gait, participants walked at a mean speed of 1.27 m/s with a step frequency of 115.6 steps/min, a mean step time of 0.52 s and mean step length of 0.66 m. Measurements of the sagittal plane ROM by IMU and MOCAP demonstrated a RMSE of 2.70° and a Pearson's correlation coefficient of 0.89 (Table 1) comparing the two measurement systems. A plot of the difference between each paired IMU and MOCAP measurement against the mean value of both (Bland–Altman) demonstrated that these differences are within two standard deviations (2SD) (Fig. 4). Comparison of frontal plane ROM measurements