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Effects of BMI and abdominal volume on the accuracy of step count obtained from a tri-axial accelerometer

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***Abstract*—Accelerometers are widely accepted as practical wearable devices capable of measuring and assessing physical activity. These devices may, however, be subject to errors which could impact on their ability to acquire an accurate step count. A limited number of studies have examined the effects of body mass index (BMI) on the accuracy of accelerometers functioning as step counters. It has been suggested that BMI may not be the best indicator of adiposity. The aim of the present study was to assess the effects of BMI and abdominal volume on the accuracy of a step count obtained from a tri-axial accelerometer. Accelerometers were placed directly onto the skin at the chest, waist and lower back of 12 participants. Participants then walked on a motorized treadmill at 0.89m/s and 1.34m/s. Analysis of the results indicated that BMI and abdominal volume did not affect the accuracy of the step count obtained from accelerometers under any conditions. Walking speed, however, had a significant effect with step count accuracy decreasing at the slower speed.**

I. Introduction

Maintaining activity into later life has been shown to be essential for both health and wellness [1]. Due to this, there has been increasing interest in the ability to accurately assess and monitor physical activity [2].

Traditionally, step count has been measured using mechanical pedometers, which in turn can provide an indication of physical activity [2]. These devices provide a measurement of the number of steps taken per day [3]. More recently accelerometers have been utilized to quantify the amount of activity undertaken. Accelerometers measure the acceleration force along a sensitive axis in up to three planes [4]. The low power consumption, small form factor and light weight properties of accelerometers make them well suited to wearable applications [5]. Further to this, accelerometers have the ability to respond to the frequency and intensity of movement and as such are commonly deemed superior to mechanical pedometers which are sensitive to both impact and tilt angle [4].

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Step count accuracy of mechanical pedometers has been shown to decrease with increasing Body Mass Index (BMI) [6]. In contrast, electronic pedometers utilizing accelerometry technology have been said to be immune to such inaccuracies [7]. There are, however, inconsistencies within the literature, with some studies reporting that BMI may have an effect on step count accuracy depending on the type of accelerometer being used [8]. The majority of these studies utilize single axis accelerometers for step detection. For these type of devices to work efficiently, it is normally attached to the hip or thigh in a constant orientation in the vertical plane. The effects of body shape and size on the accuracy of step count obtained from accelerometers has not yet been fully explored. The aim of this study was to assess the effects of abdominal volume on the accuracy of step count obtained from a triaxial accelerometer placed at various locations on the torso.

II. Related work

Feito *et al*. [8], examined the effects of BMI and tilt angle on step counts obtained from the Actigraph (single directional) and Actical (omni-directional). They found that BMI and tilt angle had a significant effect on step count obtained from the Actical but no effect on step count from the Actigraph. It was suggested that this result may have been related to the Actical's multiple directional sensitivity, which may allow it to detect subtle movements of abdominal fat in individuals with a higher BMI.

It has, however, been shown that BMI is not the best indicator of abdominal adiposity as it does not differentiate between body fat and lean muscle [9]. Furthermore, BMI cannot provide measurements of fat distribution, as depicted by Figure 1 [10]. Waist circumference or waist to hip ratio has been said to be a better indicator of abdominal fat distribution than BMI and may therefore have a greater influence on step detection accuracy [11].

Crouter *et al*. [11] examined the effects of BMI, waist circumference and tilt angle on the accuracy of mechanical (Yamax Digiwalker SW-200) and electronic (New Life NL-2000) based pedometers during treadmill and free living conditions. They found that the mechanical accelerometer became less accurate with increasing BMI, waist circumference and pedometer tilt. Nevertheless, the electronic pedometer accuracy was not affected by any of these variables. It must be noted, however, that this study only assessed single axis electronic pedometers. Furthermore, manual measurements of waist circumference are operator dependant and extremely variable in terms of repeatability [12].

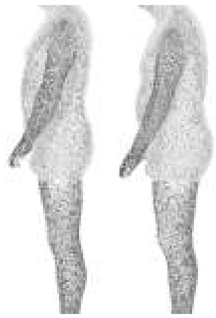

Fig. 1. Shows the body shape of two subjects both with a BMI of 30. Subtle difference in body shape and size are noticeable. The subject on the left carries much of their body volume in the chest while the subject on the right carries the majority of the fat in the abdomen and posterior.

Three dimensional body scanning allows for automatic extraction of anthropometric measurements from a true to scale body model [13]. This removes the operator error and improves reliability of measurements. Furthermore, 3D body scanning allows for assessment of body shape and volume. Unlike other volume measurement techniques, from a 3D body scan it is possible for volume to be calculated in segments (Table I). This can then be used to provide an insight into the distribution of body fat.

A. Accelerometer placement

When considering the effect of body shape and size on accelerometer accuracy the placement of the device is a key consideration. Within the literature, devices which monitor step count are commonly placed on the left or right hip (attached to the waist belt). In certain applications, however, it may be advantageous or indeed necessary to place the accelerometer on the torso [14].

The chest, for example, has been shown to provide reliable results for step counting due to its relatively constant orientation with respect to the user's direction and the fact that it provides a clean harmonized signal [15]. Placement in this location, however, requires a more complex algorithm in order to accurately count steps [5].

The lower back has also been identified as an appropriate location for accelerometer placement. Bouten *et al*. [16] chose the lower back (second lumber vertebra), as it represents a large part of the total body mass, moves during most daily activities and causes minimal discomfort to the subject.

A vast number of studies have adopted waist-placement for motion sensors as, similar to the lower back, the waist is close to the centre of mass [17]. Furthermore, this area is chosen for its ease of use from a user's point of view. In this position the device can be easily attached to or detached from a belt around the waist or the band of the trousers. This is said to impinge less on the movements of the wearer and therefore reduce discomfort [18].

From this review of previous work it may be surmised that an accelerometer placed on the torso may be more susceptible to dampening or resonance of the signal caused by increased abdominal fat which could decrease the accuracy of the device.

TABLE I
DISTRIBUTION OF BODY VOLUME IN LITRES

Body segment	Volume in Litres	Percent of total (%)
Chest	16.93	17.63
Abdomen	27.42	28.55
Pelvis	20.39	21.23
Left Arm	6.10	6.25
Left Leg	9.00	9.37
Right Arm	6.00	6.25
Right Leg	10.20	10.62
Total	**96.04**	**100.00**

Fig. 2. Shows the body volume of an elderly male. The table shows the volume of each section in litres, in addition to body section volume as a percentage of the overall body volume. From this it is possible to conclude that the majority of the body volume is located in the abdomen.

III. METHODS

Six men (n=6) and six women (n=6) volunteered to take part in the study. Individuals were recruited by the University of Wales to participate within the Design for Ageing Well project [19]. Before participating in the study all subjects were provided with participant information sheets and completed a physical activity readiness questionnaire (PAR-Q). Participants were free of cardiovascular, pulmonary and metabolic disease as reported by the PAR-Q. The average age of the participants was 65 ± 4.5 years. This work was carried out in accordance with ethics application approved by the ethics committee at University of Wales, Newport.

A. Anthopemetric measurement procedure

The NX-16 3D body scanner (TC^2, North Carolina, USA) was used to gather anthropometric measurements.

This system uses photogrammetry to rapidly produce a true to scale 3D model of the body. The system projects patterns of structured white light onto the surface of the body. The way in which the pattern is distorted by the shape of the body is recorded by 32 cameras. From this the body shape is then digitally reconstructed from a raw photonic point cloud. This then leads to a surface reconstruction of the body in 3D. White light body scanners have been shown to be consistently accurate to <1mm. Participants were scanned in tight fitting light colored underwear to allow for accurate measurement.

The percentage volume of each body segment (left leg, right leg, right arm, left arm, pelvis, chest and abdomen), were automatically captured from the body model from a custom measurement extraction parameter (MEP) file using the 3D body measurement software version 7.1 (TC^2, North Carolina, USA). BMI was calculated manually using the standard formula of $BMI=Mass(kg)/Height(m)^2$. For the purposes of BMI calculation height and weight were also measured manually.

B. Instruments

The Shimmer wireless sensor platform (Shimmer 2R, Realtime technologies, Dublin, Ireland) was used to collect accelerometer data in the study. This device has an integrated tri-axial MEMs accelerometer (Freescale MMA7361) with a selectable sensitivity range (1.5g-6g).

Data was sampled at 100Hz with a sensitivity range of 730mV/g at 1.5g. Data was streamed via Bluetooth from each device to a PC with a custom created user interface developed using BioMOBIUS 2.0 (TRIL Centre, Dublin). Data acquired from this was then saved to file for off-line processing using Matlab 2009 (Mathworks Inc., Massachusetts).

C. Test protocol

Three accelerometers were used in the course of this study. Prior to beginning the study, sensors were time synchronized. Devices were placed at the lower back (lumbar vertebrae 3-4), sternum (below the chest muscles) and waist (anterior axilliary line). In order to provide a standardized test setup all accelerometers were attached directly to the skin in the vertical plane using medical grade adhesive tape and double sided adhesive pads.

Participants were then instructed to walk on a motorized treadmill at 0.89m/s and 1.34m/s for 3 minutes each. These walking speeds were selected as they represent average walking speeds for the older population [20]. Between each exercise bout, participants were asked to rest for one minute. All sensors were then removed and re-attached and the experimental procedure repeated.

A video camera was used to record each of the walking bouts. From this the actual sum of steps taken was then calculated and used as the gold standard.

D. Statistical analysis

To allow for analysis of the effect of BMI, participants were categorized according to the World Health Organization's BMI categories of: normal (18.5-25 kg/m^2), overweight (25-29.9 kg/m^2) and obese (>30 kg/m^2) [21].

The volume of each body segment was extracted automatically from the body scans. The abdominal volume was then compared across the BMI categories.

One way analysis of variance was conducted in order to determine the relationship between BMI, abdominal volume and gender.

Step count was calculated from each of the accelerometer signals using a simple step detection algorithm utilizing a low pass filter, threshold, derivative and peak detection functions. The calculated step count from each device was then compared with the actual number of steps from the video. The percentage error was calculated using equation 1. Were C_s is the number of steps from the accelerometer and A_s is the actual number of steps from the video.

$$\text{Percentage accuracy} = 1 - \left(\frac{C_S - A_S}{A_s}\right) \times 100 \quad (1)$$

A two way (BMI vs. Placement site) repeated measures analysis of variance was performed to determine the effect of BMI on step count accuracy of each device at both walking speeds. Post processing using pairwise comparison (Bonferroni adjustment) was performed to detect significant differences.

A two way repeated measures analysis of variance was also carried out to assess the effect of abdominal volume on step count accuracy.

SPSS for Windows version 17.0 (SPSS Inc., Chicago) was used to carry out all statistical analysis. The overall significance level was set to α=0.05.

IV. Results and Discussion

A. Comparison of BMI and Abdominal volume

Abdominal volume was significantly different for the normal, overweight and obese groups (p=0.027). As illustrated by Figure 3, abdominal volume increased with BMI (R^2=0.8297).

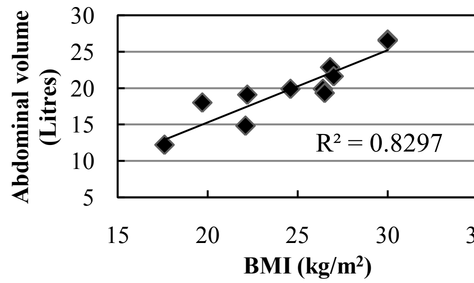

Fig. 3. Plot of abdominal volume against BMI. This illustrates a correlation showing that abdominal volume increases with BMI.

B. Step count accuracy.

Category of BMI did not significantly affect step count accuracy at either 0.89m/s (p=0.115) or 1.34m/s (p=0.560). Figure 4 shows the average percentage accuracy for each BMI category at 0.89m/s and 1.34m/s, respectively. These results are consistent with the published literature [2][3].

Furthermore BMI category did not have a significant effect on the accuracy of accelerometers placed at the lower back (p=0.689), sternum (p=0.787) or waist (p=0.622).

Abdominal volume also had no impact on the accuracy of step count from the accelerometers at any location or speed. This was due to the high correlation of abdominal volume to BMI.

There was, however, a small yet significant difference between step count accuracy obtained at 0.89m/s and 1.34m/s (p=0.003). Again this finding is consistent with the literature which previously reported that accuracy decreased at slower walking speeds [4]. This is most likely due to the lower amplitude acceleration signal produced by walking at the slower speed. In this case, step count accuracy decreased on average from 99.77% at 1.34m/s to 99.64% at the lower speed of 0.84m/s.

V. Conclusion

This study has established that neither BMI nor abdominal volume had an effect on the step count accuracy obtained from a tri-axial accelerometer placed at the lower back, sternum and waist. This adds some clarity to the current inconsistency within the literature. Changes in walking speed had a small, however, significant effect with step count accuracy decreasing at the lower speed. This may, however, be dependent on the type of step detection algorithm and therefore further investigations into this finding are required. Further to this, results demonstrated a positive correlation between abdominal volume and BMI within the participants studied. This information may prove beneficial when designing a wearable based system for physical activity monitoring. As it illustrates that an accelerometer can be placed in a variety of locations around the torso and still function accurately to measure steps across a range of body shapes and sizes.

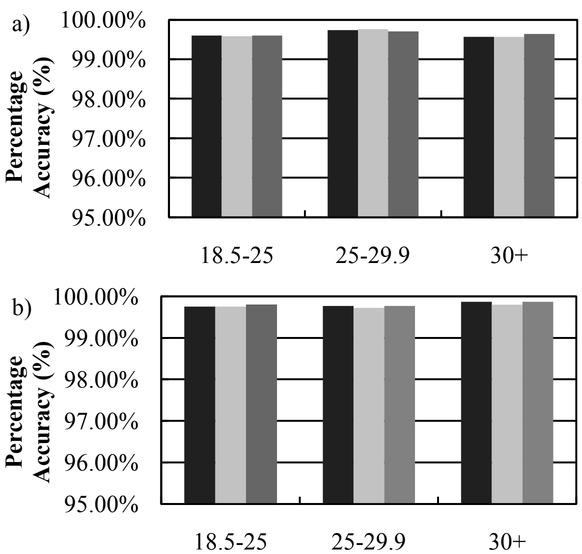

Fig. 4. Effect of BMI on the accuracy of steps obtained from accelerometers placed at the ■ lower back, ■ sternum and ■ waist at the anterior axilliary line whilst walking at a) 0.89m/s and b)1.34m/s.

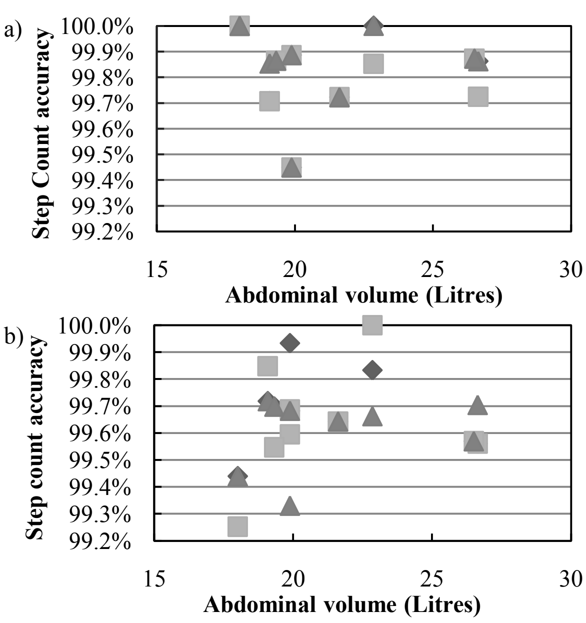

Fig. 5. Effect of Abdominal volume on the accuracy of steps obtained from accelerometers placed at the ♦lower back, ■Sternum and ▲waist at the anterior axilliary line whilst walking at a)0.89m/s and

VI. References

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