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Short communication

Use of ‘wearables’ to assess the up-on-the-toes test

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ABSTRACT

The mechanical output at the ankle provides key contribution to everyday activities, particularly step/stair ascent and descent. Age-related decline in ankle functioning can lead to an increased risk of falls on steps and stairs. The rising up-on-the-toes (UTT) 30-second test (UTT-30) is used in the clinical assessment of ankle muscle strength/function and endurance; the main outcome being how many repetitive UTT movements are completed. This preliminary study describes how inertial measurement units (IMUs) can be used to assess the UTT-30. Twenty adults (26.2 ± 7.7 years) performed a UTT-30 at a comfortable speed, with IMUs attached to the dorsal aspect of each foot. Use of IMUs' angular velocity signal to detect the peak plantarflexion angular velocity (p-fAngVel$_{peak}$) associated with each repeated UTT movement indicated the number of UTT movements attempted by each participant. Any UTT movements that were performed with a p-fAngVel$_{peak}$ 2SD below the mean were deemed to have not been completed over a sufficiently ‘full’ range. Findings highlight that use of IMUs can provide valid assessment of the UTT 30-second test. Their use detected the same number of attempted UTT movements as that observed by a researcher (average difference, −0.1 CI, −0.2 – 0.1), and on average 97.6 ± 3.1% of these movements were deemed to have been completed ‘fully’. We discuss the limitations of our approach for identifying the movements not completed fully, and how assessing the consistency in the magnitude of the repeated p-fAngVel$_{peak}$ could be undertaken and what this would indicate about UTT-30 performance.

1. Introduction

Age-related decline in muscle strength and function (Jan et al., 2005; Pijnappels et al., 2008b), compromises everyday functional ability (Stathokostas and Vandervoort, 2016). The ankle's mechanical output has substantial contribution to activities such as walking and step/stair ascent and descent (Riener et al., 2002; Buckley et al., 2013). Therefore, assessing ankle strength is undertaken to identify those with compromised everyday mobility and hence an increased falling risk (Flanagan et al., 2005; Pijnappels et al., 2008a; Cattagni et al., 2014; Ema et al., 2016). The rising up-on-the-toes (UTT) 30-second test (UTT-30) assesses ankle muscle strength/function and endurance (Hébert-Losier et al., 2017; Sman et al., 2014). The test involves rising UTT as many times as possible within 30-seconds, and is performed using just the dominant limb (Lunsford et al., 1995; Jan et al., 2005; Chitre and Prabhu 2017; Österberg et al., 1998; Kasahara et al., 2007); though in older participants it is commonly undertaken bipedally (André et al., 2016; Hébert-Losier et al., 2009; Fujisawa et al., 2015; Fujiwara et al., 2010; Monteiro et al., 2017).

To encourage the patient to complete each repetition over a ‘full’ range of motion (ROM), i.e. comparable ROM as that determined during a single controlled UTT movement, various monitoring devices have been used (Lunsford et al., 1995; Jan et al., 2005; Sman et al., 2014; André et al., 2016). None of these approaches have been adopted widely and all require an observer to determine how many repetitions are completed. Whilst the inter-rater reliability for determining the number of repetitions has been shown to be high (ICC = 0.93–0.96) (André et al., 2016), a poorer intra-rater reliability (ICC = 0.79–0.84) (André et al., 2016), suggests that counting errors occur. There is a need for digital approaches to inform a more reliable approach to UTT-30 assessment.

This preliminary study investigates the use of inertial measurement units (IMU) to assess the UTT-30. Specifically, we demonstrate how IMU-derived plantarflexion angular velocity (p-fAngVel) could help inform a more reliable/valid approach to determine the number of UTT repetitions completed. We also describe an approach for evaluating the magnitude of the repeated peaks in p-fAngVel (p-fAngVel$_{peak}$) to automatically determine how many of the attempted UTT movements were completed ‘fully’.

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2. Methods

2.1. Participants

Twenty healthy adults took part (13 males, 7 females; mean ± SD age: 26.2 ± 7.7 years, height: 1.7 ± 0.1 m and mass: 69.9 ± 16.1 kg). All participants gave informed consent. The study received local research ethics approval, and the tenets of the Declaration of Helsinki were observed. Participants wore comfortable clothing and flat-soled shoes (trainers) during testing.

2.2. Protocol

As part of a larger data collection protocol participants were instructed to complete the following:

1. 20-seconds standing;
2. UTT-30; participants were instructed to complete UTT movements at a comfortable speed as many times as possible, and over what they perceived was a full range, ensuring the heel contacted the ground between repetitions, Fig. 1(a). An observer counted/recorded the number of repeated UTT movements.
3. 20-second standing;
4. Single-UTT (hold for 5 s); participants were instructed to rise-up-on-the-toes as fast as possible and hold position until indicated to "return" to standing. Data not presented here.
5. 20-seconds standing.

2.3. Data collection

Two IMUs (AX6, Axivity Ltd, Newcastle, UK) were attached to the upper surface of each shoe, approximately 4 cm anterior of the shin: only data for the left foot is analysed here. Using the proprietary software OmGUI (Github DigitalInteraction, 2020), raw data (100 Hz) were downloaded and exported ('.cwa' format).

3. Data processing and analysis

3.1. Segmentation (see Fig. 1)

IMU data were uploaded into MATLAB® (MathWorks, Inc., Natick, US) where the tri-axial angular velocity data (x,y,z) were initially filtered (second-order Butterworth low pass filter with a cut off frequency of 20 Hz) and then plotted. The UTT-30 data were visually identified in the data-stream from the easily identifiable repetitive angular velocity patterns from the UTT-30 (related to the repeated foot movements), that was separated by the two 20 s periods of static standing, Fig. 1(b). Once the UTT-30 data were segmented, the following parameters were determined:

1. *Number of UTT movements attempted:* Each UTT movement was identified by a distinct peak (local maxima) in left foot's p-fAngVel (the p-fAngVel of the left and right feet were comparable). The number of p-fAngVel$_{peak}$ identified indicated the number of UTT movements attempted.
2. *Number completed 'fully':* An initial-mean and SD p-fAngVel$_{peak}$ across the repeated UTT movements were calculated. The number of angular velocity peaks remaining after peaks below 2SD of the mean were removed, indicated how many UTT movements were completed 'fully'.
3. *Mean and SD in p-fAngVel$_{peak}$:* Each participant's mean (±SD) p-fAngVel$_{peak}$ were calculated from the fully completed movements.

3.2. Statistics

Bland-Altman analysis determined the agreement between the number of UTT movements determined by analysis of the IMU-data to that counted by observer.

4. Results

All participants were able to complete the UTT-30 and showed no signs of excessive discomfort or fatigue during the assessment. The number of UTT movements completed by each participant, as determined by the observer or by analysis of the IMU's data, are provided in Table 1. Additionally, each participant's mean (±SD) p-fAngVel$_{peak}$ for the UTT movements deemed fully completed are shown in Table 1.

4.1. Number of UTT movement attempted

The number of movements detected from the IMU (group-average = 23.5 ± 9.8) was similar to the numbered observed (group-average = 23.7 ± 9.7). The agreement between the number detected by IMUs to that observed was −0.05 (CI, −0.49 – 0.39).

4.2. Number completed 'fully'

Fig. 2 presents exemplar data for one participant showing the UTT

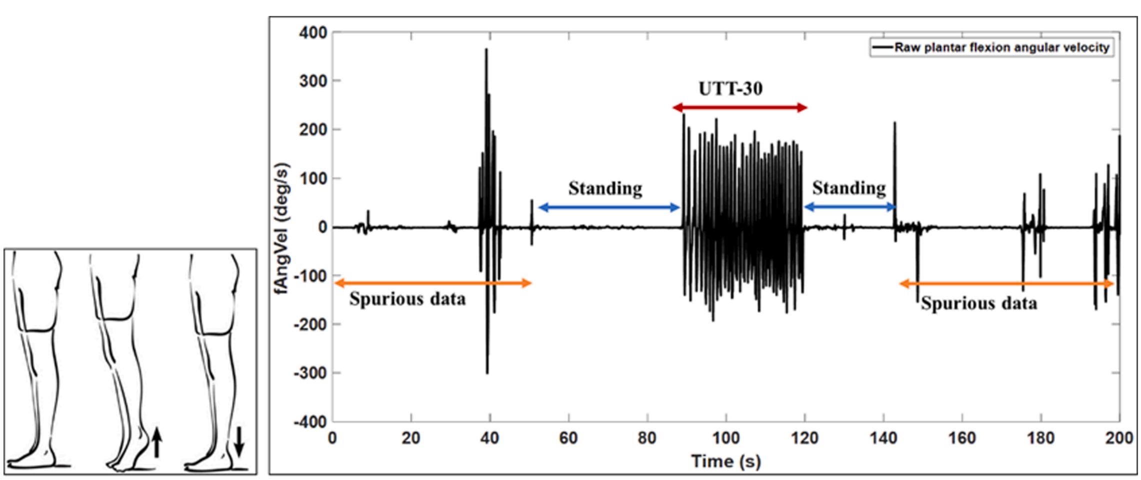

Fig. 1. (a) Illustration of UTT-30: stationary standing, rising to toes and returning to neutral position, respectively; (b) identification of the UTT-30 data in the data-stream.

Table 1
Number of UTT movements observed or detected for each participant, along with their mean peak plantarflexion angular velocity (p-fAngVel$_{peak}$) when rising UTT.

Participant	No. UTT movements			'fully' completed	mean (±SD) p-fAngVel$_{peak}$ (°/s)
	Observer	IMU	diff		
1	29	29	0	29	136 (12)
2	36	36	0	34	136 (16)
3	12	12	0	12	155 (18)
4	24	24	0	23	153 (28)
5	36	36	0	35	280 (27)
6	31	31	0	30	173 (21)
7	19	19	0	17	203 (10)
8	28	28	0	26	183 (17)
9	21	21	0	21	153 (21)
10	23	23	0	22	132 (11)
11	26	26	0	25	182 (17)
12	18	18	0	18	146 (11)
13	17	17	0	16	90 (10)
14	12	12	0	12	91 (18)
15	18	18	0	18	121 (21)
16	15	15	0	15	103 (9)
17	18	18	0	18	162 (20)
18	17	16	−1	16	70 (18)
19	19	19	0	19	130 (22)
20	52	52	0	52	175 (29)
Mean	23.6	23.5	0.1	22.9	148.8 (17.8)
SD	9.7	9.8	0.2	9.6	46.4 (6.1)

movements attempted and fully completed. On average 0.6 ± 0.8 movements per participant were deemed to have not been completed fully, highlighting that on average 97.6 ± 3.1% of the movements were 'fully' completed.

4.3. Mean and SD in p-fAngVel$_{peak}$

After discounting movements not completed 'fully', the group-average mean and SD in p-fAngVel$_{peak}$ across the repeated UTT movements was 148.8 ± 46.4°/s (range 70.1 – 280.4°/s) and 17.8 ± 6.1°/s (range 8.5 – 29.0°/s), respectively.

5. Discussion

This preliminary study highlights how IMUs can be used to assess the UTT-30. Findings demonstrate that IMUs can provide a reliable/valid digital assessment of the UTT-30 by detecting the same number of UTT movements attempted during the test as that counted by an observer, and importantly their use provides an objective means to discount any UTT movements that are not completed 'fully'.

Identifying UTT movements that might not be completed 'fully' is difficult to do via observations. Previous studies using or evaluating the UTT-30, have implemented various devices to evaluate the number of UTT movements 'fully' completed. For example, Lunsford and colleagues used an electrogoniometer to measure ankle ROM, and set a target ROM of 50% of each participant's ROM determined prior to starting the test (Lunsford et al., 1995). UTT movements with a ROM at or above this threshold were deemed to have been executed fully. Another study used a height-adjustable elastic band device placed beneath the heel. The height of the band was adjusted to the height of the heel during a UTT movement completed over a full ROM. When performing the UTT-30, failure of the heel to clear the band on two consecutive occasions ended the test (Sman et al., 2014). Elsewhere, a foam-board placed above the participant's head, was adjusted to the height attained when completing a controlled comfortably-high as possible single UTT movement: participants were asked to touch the board with their head when performing the UTT-30 (André et al., 2016). Whilst these approaches may help improve the repeatability of performing and assessing the UTT-30, they require an observer to multitask by (i) monitoring the device and/or person as s/he completes the UTT-30, while (ii) making judgements regarding how many UTT movements are completed 'fully'. In the present study, the use of IMUs provided a digital and contemporary determination of how many UTT movements were attempted and how many were completed 'fully'. Additionally, use of the IMU negated any need to monitor the person, or device, and the need for adjusting the device to the participant prior to the test. This highlights that evaluation of the UTT-30 could be speedily undertaken with IMUs, which suggests their use is suitable in a broad range of environments. Their disadvantage is that that they provide no feedback to the patient to encourage them to complete each UTT movement over the full ROM. Such a drawback could be negated by giving the patient extra guidance about performing the test and verbal encouragement during the test. Moreover, future work could develop a system to provide real-time feedback from the accelerometer that could be presented to the participant during training/rehabilitation sessions.

After discounting the UTT movements not completed fully, we determined the mean p-fAngVel$_{peak}$ for the remaining movements. This measure portrayed how quickly on average an individual rose up-on-to-the-toes. This metric is not typically evaluated when administering the UTT-30 but may provide useful information about ankle functionality,

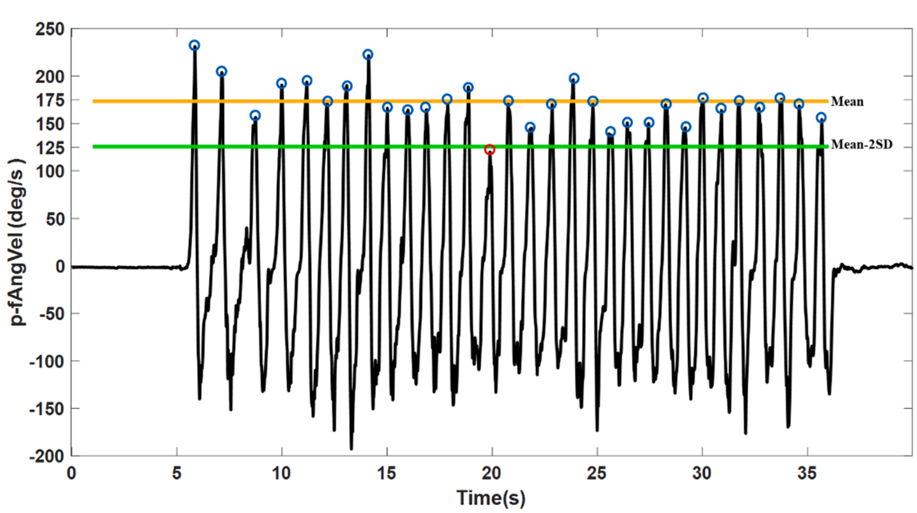

Fig. 2. Exemplar p-fAngVel trajectory showing fully completed movements. (a) identification of local maxima in p-fAngVel (circled in blue) for each repeated UTT movement, (b) identification of peaks falling below 2SD of the initial-mean (circled in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

though future research is needed to confirm this.

It is important to note that our approach of determining a p-fAngVel$_{peak}$ to identify each UTT movement, also provided indication of UTT speed but not its ROM. We used the criteria that UTT movements that were not completed 'fully' were those that yielded a p-fAngVel$_{peak}$ that was 2SD below the initial-mean p-fAngVel$_{peak}$ across the repeated UTT movements. Because our participant group were young and healthy, we supposed the variability in p-fAngVel$_{peak}$ would be relatively low. Thus we reasoned that having a p-fAngVel$_{peak}$ 2SD below the initial-mean p-fAngVel$_{peak}$ would be associated with a UTT movement that was incorrectly/partly completed and thus one performed with reduced ROM rather than one simply performed at a reduced speed (by implication, a threshold of $<$ 2SD from the mean would occur $\leq$ 5% of the time). However, evaluation of the magnitude of the speed of movement cannot be the best way to identify UTT movements that are not completed over a full ROM, particularly as p-fAngVel$_{peak}$ variability is likely to be much higher for older adults and/or those with compromised everyday mobility. Hence future work using IMUs could consider determining the area under the angular velocity curve to determine the change in angular displacement associated with each UTT movement, to identify movements not completed 'fully'. Alternatively, instead of using threshold-criteria to identify UTT movements not completed fully, we propose that the same type of criteria should be used to determine UTT-30 consistency by simply determining how many UTT movements, in percentage terms, had a p-fAngVel$_{peak}$ that was within 2SD of the mean p-fAngVel$_{peak}$. This approach eliminates the need to identify movements not completed fully. Measuring consistency in this way could be done for a range of thresholds, e.g. 1SD, 1.5SD and 2SD of the mean pf-AngVel$_{peak}$. For the current participant-group, the average (and range in) consistency in reproducing a pf-AngVel$_{peak}$ within 1SD, 1.5SD and 2SD of the mean pf-AngVel$_{peak}$ was 84% (range, 74–92%), 94% (range, 89–100%), and 98% (range, 89–100%) respectively. No doubt such consistency would be lower for older adults and/or those with with compromised everyday mobility. It would also be straightforward to determine the variability (e.g. standard deviation) in p-fAngVel$_{peak}$ for the UTT-30; again without a need to eliminate movements not completed fully. Lower variability/higher consistency would highlight better repeatability in speed of rising-to-the-toes across the repeated UTT movements (and hence better control). Evaluating changes in the variability in p-fAngVel$_{peak}$ and/or in the different threshold ranges in p-fAngVel$_{peak}$ consistency when performing the UTT-30 may have as much clinical relevance as determining how many UTT movements are performed within the 30 s period: but again these are topics for future research to explore.

This preliminary study showcases the use of low-cost IMU's for UTT-30 assessment. Other preliminary work has shown they can be used to differentiate rising-to-the-toes performance in Parkinson's patients and controls (Bonora et al., 2017). However limitations for their more widespread use remain. For example, IMUs have a basic data capture and export functionality. Accordingly, our future work will involve creation of an automated approach for automatically detecting and extracting relevant outcomes from IMUs to provide evaluation of the UTT-30 for clinical use. Additionally, a more rounded investigation of the UTT-30 outcomes presented here should be conducted. Accordingly, as part of our ongoing work we will critically evaluate the IMU UTT-30 approach compared to reference standard equipment.

CRediT authorship contribution statement

Sarah Aruje Zahid: Methodology, Investigation, Writing – original draft. **Yunus Celik:** Investigation, Software, Visualization. **Alan Godfrey:** Conceptualization, Software, Writing – review & editing. **John G Buckley:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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