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Novel, clinically applicable method to measure step-width during the swing phase of gait

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Keywords: gait, swing phase, step-width, inertial measurement unit, wearable, optical sensor

Abstract

Objective: Step-width during walking is an indicator of stability and balance in patients with neurological disorders, and development of objective tools to measure this clinically would be a great advantage. The aim of this study was to validate an in-house-developed gait analysis system (Striton), based on optical and inertial sensors and a novel method for stride detection, for measuring step-width during the swing phase of gait and temporal parameters. Approach: The step-width and stride-time measurements were validated in an experimental setup, against a 3D motion capture system and on an instrumented walkway. Further, test-retest and day-to-day variability were evaluated, and gait parameters were collected from 87 elderly persons (EP) and four individuals with idiopathic normal pressure hydrocephalus (iNPH) before/after surgery. Main results: Accuracy of the step-width measurement was high: in the experimental setup mean error was 0.08 \pm 0.25 cm (R = 1.00) and against the 3D motion capture system 0.04 \pm 1.12 cm (R = 0.98). Test-retest and day-to-day measurements were equal within \pm 0.5 cm. Mean difference in stride time was $-0.003 \pm 0.008$ s between Striton and the instrumented walkway. The Striton system was successfully applied in the clinical setting on individuals with iNPH, which had larger step-width (6.88 cm, n = 4) compared to EP (5.22 cm, n = 87). Significance: We conclude that Striton is a valid, reliable and wearable system for quantitative assessment of step-width and temporal parameters during gait. Initial measurements indicate that the newly defined step-width parameter differs between EP and patients with iNPH and before/after surgery. Thus, there is potential for clinical applicability in patients with reduced gait stability.

1. Introduction

Gait disorders are common in individuals with neurological or musculoskeletal diseases. In clinic, however, it is often difficult to in detail assess the level of gait impairment due to the lack of reliable and objective tools. Clinically, gait function is often visually assessed using coarse scales, including estimates of, for example, gait initiation, step length and height, step symmetry and steadiness evaluated as adequate or not (Tinetti 1986). Other types of gait quantifications are based on discrete, descriptive levels ranging from, for example, ‘normal’ to ‘wheel chair bound’ (Hellström et al 2012) or use of stopwatches to measure gait speed and endurance (Guyatt et al 1985, Tinetti 1986, Guralnik et al 1994). Visual ratings have been found to have low intra- and inter-observer reliability, thus affecting the objectivity of the assessments and consequently the accuracy of diagnosis and follow-up (Muro-de-la-Herran et al 2014). In contrast to the assessment in clinic, the scientific movement analysis research utilizes advanced instruments, e.g. treadmills, 3D motion capture systems or instrumented walkways to gain a detailed picture of gait function. Since most of these instruments are expensive, require large specialized laboratories and specially trained personal, they are seldom suitable for daily clinical investigations.

Wearable sensors, based on inertial measurement units (IMU), are becoming increasingly popular within movement analysis research. Due to their independence of location, relative simplicity and low price, they...
have been suggested to be useful for assessing the quality of gait in everyday clinic (Trojaniello 2014b, Cereatti et al 2014, Anwary et al 2018). There is, however, a gap between the clinical studies showing promising results when applying IMU systems to assess gait, and the actual implementation of the systems into everyday health care (Vienne et al 2017). To bridge this gap, the equipment needs to be fast and easy to apply, yet precise enough to answer the specific questions relevant for the group of patients being investigated or treated.

IMUs can detect motions that may be used to calculate temporal and spatial gait parameters such as step and stride time, step length, foot to floor clearance and various joint angles in the lower extremities. Of these, spatial parameters are less accurate since they require integration of IMU sensor data which suffer from both offset and drift problems, resulting in uncertainty in the final position data. To overcome these problems sensor fusion techniques of IMU data are used (Madgwick et al 2011, Rouhani et al 2011). The reliability and validity of these sensors have been thoroughly investigated for various clinical applications in recent years (Mariani et al 2010, Rampp et al 2014, Taylor et al 2017, Panciani et al 2018, Öhberg et al 2019), and systems based on IMUs can now be considered stable enough to assess most temporal and spatial gait parameters within acceptable limits (Cuesta-Vargas et al 2010, Muro-de-la-Herran et al 2014, Caldas et al 2017).

Impaired gait is a typical symptom in patients with the neurological disorder idiopathic normal pressure hydrocephalus (iNPH). The gait pattern is described as slow, broad based, shuffling and short-stepped (Stolze et al 2001, Relkin et al 2005). Commonly, step-width during walking is increased in this patient group (Allali et al 2013, Selge et al 2018) and a widened base of support is part of the diagnostic guidelines for the disease (Relkin et al 2005). Step-width is, in general, an indicator of stability and balance during walking, and has been found to be important for predicting falls (Ko et al 2007, Nordin et al 2010), for assessment of swing leg circumduction (Shorter, Wu, and Kuo 2017) and for locomotive control (Owings and Grabiner 2004). The parameter is however difficult to assess using the visual rating scales clinically available today, thus more objective and quantitative measures are needed. IMUs are less suitable since it is difficult to relate the absolute position of two different IMUs mounted on separate body segments to each other (Rebula et al 2013, Bertuletti et al 2017). One recent attempt based on IMUs proving this point resulted in a 95% confidence interval (CI) of ±6 cm (Bland–Altman plot)(Teufl et al 2019). Other techniques include shoe mounted distance sensors to measure intra foot distance, i.e. triangulating infrared sensors and infrared time of flight sensors (Trojaniello et al 2014, Bertuletti et al 2017). A disadvantage with shoe mounted sensors is the need of a target mounted on the opposite shoe, making the equipment shoe dependent and thus clinically impractical.

To comply with the healthcare’s need for time-efficient, easy to use and disease specific measurement instruments, we have developed a simple leg mounted system based on a fusion of optical and IMU sensors. In addition to gait parameters commonly assessed, an optical distance sensor was placed on the inside of one shank measuring the distance between the shanks to assess step-width during the swing-phase of the gait. The aim of this study was to validate this method of step-width assessment, together with a new method for step detection based on the peak angular swing velocity. An additional aim was to present the newly defined step-width parameter in an elderly population, and to demonstrate applicability on a group of patients with iNPH before and after shunt surgery.

2. Method

2.1. Gait assessment system

The in-house developed system, Striton, figure 1, includes two IMUs (ADIS16448, Analog Devices, USA), an optical infrared triangulating distance sensor (GP2D120, Sharp corporation, Japan) and one data acquisition (DAQ) unit consisting of a microprocessor, a real time clock, a Bluetooth module, two 3.7 V 1.3 Ah Li-ion batteries and a micro-SD card, figure 1. Running time on batteries is 19 h. The weight of the DAQ unit and sensors is 150 and 100 g respectively. Sampling frequency was set to 256 Hz with 16-bit resolution for all sensors, with 70 Hz hardware filtering for the IMUs. The optical sensor has an analog output signal with an absolute position of two different IMUs mounted on separate body segments to each other (Rebula et al 2013, Bertuletti et al 2017). One recent attempt based on IMUs proving this point resulted in a 95% confidence interval (CI) of ±6 cm (Bland–Altman plot)(Teufl et al 2019). Other techniques include shoe mounted distance sensors to measure intra foot distance, i.e. triangulating infrared sensors and infrared time of flight sensors (Trojaniello et al 2014, Bertuletti et al 2017). A disadvantage with shoe mounted sensors is the need of a target mounted on the opposite shoe, making the equipment shoe dependent and thus clinically impractical.

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In gait analysis, the heel strike is most often used to determine the initiation of a step. If the gait is normal or close to normal the heel strike is generally easy to identify based on the accelerometer signal. In patients with neurological disorders this method may not always work, since a shuffling gait with reduced floor clearance makes the heel strike inappreciable or absent (Gouwanda and Gopalai 2015). To solve this problem, Striton uses the peak of the swing angular velocity from the gyroscope (z-axis, in sagittal plane) during the mid-swing of the step as the trigger for step detection, figure 3. A program based on the software LabVIEW (LabVIEW 12.0 National Instruments, Austin, TX, USA) was developed and used for subsequent analysis. To detect the peaks, the built in LabVIEW peak detector based on an algorithm that fits a quadratic polynomial to sequential groups of data points was used.
2.2. Calibration and validation in experimental setup
The optical sensor output and the measured distance was approximated by an inverse proportional relationship, making the resolution higher at shorter distances, figure 4. To maximize the precision in the clinically relevant region, dynamic calibration was performed for distances 3.5–22 cm using the table of a milling machine equipped with a scale with a resolution of 0.005 mm resolution (Sony, Magnescale LH10, Japan). The sensor was setup facing a target, and measurements were attained with 2 cm increments at a speed of 360°/s. Curve fitting was applied according to

$$\text{Distance [cm]} = 11.00 \times (\text{sensor output [volt]})^{-1.11}, \ R^2 = 0.997.$$ 

The optical sensor calibration was validated in an experimental pendulum setup, i.e. a wooden stick which could be horizontally swung to simulate a gait pattern at three different paces. A metronome was used to keep the pace at 72, 96 and 120 swings min⁻¹, simulating slow, normal and fast walking. Five predefined distances (equally spaced from 5 to 20 cm) between the sensor and a simulated leg was used, figure 5. The simulated leg was covered with the same white curved plastic material as used during measurements on human subjects. The sensor was swung repeatedly past the simulated leg (n = 30) while measuring the optical output at all pre-set distances.

2.3. Participants
In this study, three groups were included. The first group consisted of ten healthy individuals (HI, 36.5 ± 10.5 years, five females) that participated in the validation of Striton versus the optical system. The second group consisted of 87 healthy elderly persons (EP, 70 years old, 50 females) that participated in the validation of the stride-time measurements. Ten out of these 87 EPs (six females) were further randomly
recruited for analysis of test-retest and day-to-day variability of step-width. Finally, a patient group consisting of four patients with iNPH (73 ± 3.2 years, three females) were included in a pre- and post-operative clinical evaluation.

The HI were recruited among personnel at University Hospital of Umeå, Sweden, and exclusion criteria were all known conditions with potential impact on gait.

The EP were consecutively recruited as part of a larger study (Healthy Aging Initiative at Umeå University, Sweden1) to which every community dwelling person is invited upon turning 70 years old, resulting in 100 recruited persons. Exclusion criteria from further analyses were all known conditions with potential impact on gait performance (Parkinson’s disease (n = 1), stroke (n = 8), arthrosis in knee (n = 1) and pain when walking (n = 3)). Based on the remaining 87 EP, step-width and stride-time were analyzed. One further person was excluded from the validation of stride-time due to a damaged data file.

The four patients with iNPH were included in conjunction with standardized preoperative and postoperative (three months after surgery) clinical investigations. Inclusion criteria were recommendation to shunt surgery according to the standard procedure at the hospital which is in accordance with the iNPH guidelines (Relkin et al. 2005) and being able to walk 20 meters without support. Exclusion criteria were Mini Mental State Examination ≤20 points or secondary NPH.

All participants gave their informed written consent to participate in the study, which was approved by the local Ethical Review Board (Dnr 09–120 M/2014-246-32 M/2018-155-31 M).

2.4. Test protocols
For all protocols, Striton was mounted in accordance with figure 2(a) and all individuals were barefoot during the assessments. Once a recording with Striton was started with the remote control, the person initially stood still to ensure to include only complete steps in the analyses. Then told to walk straight forward towards a target in front of them.

Protocol 1 (Step-width validation, HI): Striton step-width was validated against a 3D motion capture system based on eight cameras with a sampling frequency of 60 Hz (Oqus®, Qualisys AB, Gothenburg, Sweden). Striton and two reflective markers were placed on the HI according to figure 2(b). Each HI walked approximately 4 meters in total 22 times; 11 times normally and 11 times with increased step-width. Step-width was calculated as the mean of each 4-meter walk. For Striton, step-width was defined as the shortest distance measured by the distance sensor during each step (i.e. one reading each step). Step-width from 3D motion capture system was defined as the horizontal distance between the reflective markers in the frontal plane when the markers were at the same horizontal position in the sagittal plane (i.e. one reading each step). The first step was used for step synchronization.

Figure 6. (a) Step-width sensor validation in experimental pendulum setup at 96 steps/min (p < 0.001), 30 repetitions at each distance, mean SD = ± 0.07 cm (n = 4 distances). (b) Linear regression between step-width measured with Striton and the 3D motion capture system (p < 0.01, n = 220, each dot is the mean width of one 4 m walk).

Protocol 2 (Stride-time validation, EP): Stride-time was validated against a 6.09 m long instrumented walkway (GAITRite®, NJ, USA). EPs walked two times at their normal preferred speed on the instrumented walkway with the Striton system measuring simultaneously. For each walk, mean stride-time from the instrumented walkway was compared to the mean stride-time from the Striton system. In order to exclude the acceleration phase, the person started walking from a point 2 m before the instrumented walkway.

Protocol 3 (Test-retest, subset of EP): Ten out of the 87 EPs (six females) were randomly recruited for analysis of test-retest and day-to-day variability of step-width. The test-retest measurements were separated by two hours and the day-to-day measurements by one week. All measurements were performed by the same operator. The EPs were instructed to walk at their normal preferred speed for 20 meters two times at both occasions.

Protocol 4 (Clinical validation, iNPH patients): For the clinical validation, the Striton system was mounted and the iNPH patients were instructed to walk 20 meters at their normal preferred speed in a straight corridor, two times.

2.5. Statistics
All data were tested for normality using the Shapiro–Wilk test. For comparison between Striton, the 3D motion capture system and the instrumented walkway, Pearson correlations with two-tailed significance tests (PASW Statistics, version 18.0.3, SPSS Inc. Chicago, IL) and Bland–Altman plots were applied. Variability in gait was reported as coefficient of variation (CV) calculated as within-subject SD/within-subject mean. The analyses of test-retest and day-to-day variation were performed according to Lakens (Lakens 2017) using two one-sided t-tests for equivalence (TOST, Excel script 2) and paired t-tests. In the TOST test, upper (ΔU) and lower (ΔL) equivalence bounds were specified based on the values accepted as clinically equal between tests. Here, ΔL and ΔU were chosen as ±0.5 cm. For all tests, α < 0.05 was required for statistical significance.

3. Results

3.1. Validation in experimental setup and against 3D motion capture system
There was a high correlation between actual and measured distance at all paces in the experimental pendulum setup, mean error ± 0.08 cm, figure 6(a). The mean SD was highest at the highest pace (mean ± 0.25 cm at 5–20 cm and 120 swings min⁻¹), and highest at 20 cm distance (±0.39 cm at 120 swings min⁻¹).

2 https://osf.io/q253c/
Figure 7. Bland–Altman plot comparing step-width measured by the Striton and the 3D motion capture system for persons walking with normal and increased step-width. Bias was +0.04 cm and the dotted lines show 95% CI (±1.12 cm), n = 220.

High correlation and a slope close to one (R = 0.98, k = 0.96, n = 220, figure 6(b)) was also found between Striton and the 3D motion capture system. The Bland–Altman plot showed a bias of 0.04 cm and the upper/lower limits of the 95% CI were 1.16 and −1.08 cm respectively, figure 7.

3.2. Test-retest and day-to-day variability
The test-retest investigation on 10 persons in the EP group resulted in a mean difference of 0.20 ± 0.44 cm (baseline: 5.31 ± 0.93 cm, n_{steps} = 639, after two hours: 5.11 ± 0.68 cm, n_{steps} = 610) in step-width. The corresponding day-to-day difference was 0.03 ± 0.39 cm (baseline: 5.31 ± 0.93 cm, after one week: 5.28 ± 0.96 cm, n_{steps} = 591). Step-width was significantly equal within ±0.50 cm when tested accordingly to the TOST procedure (p < 0.01) in both cases.

3.3. Step-width in EP and patients with iNPH
EP (n = 87, n_{steps} = 5065) had a mean step-width of 5.22 ± 0.89 cm. Step-width variability was CV = 17.1%. Males had a larger step-width than females, 6.21 ± 1.03 cm (n = 38, n_{steps} = 2118) and 4.46 ± 0.77 cm (n = 49, n_{steps} = 2947, p < 0.001) respectively, figure 8(a).

The individuals with iNPH had a mean step-width of 6.88 cm before and 6.30 cm after surgery, figure 8(a). Following surgery, step-width was reduced, and variability decreased or sustained in three out of four cases, figure 8(b).

3.4. Comparison of stride time between striton and instrumented walkway
Stride times measured with Striton and the instrumented walkway correlated strongly (R^2 = 0.99, p < 0.01, n_{strides} = 711), figure 9. The Bland–Altman plot showed a bias of −0.003 s, and the limits of the 95% CI were 0.013 and −0.019 s respectively, figure 10.

4. Discussion
In this paper, a novel in-house built wearable system (Striton) for gait analysis including the measurement of step-width during the swing phase of gait was validated. Validations were made against an experimental setup, a 3D motion capture system, an instrumented walkway as well as repeatedly on healthy elderly. The newly defined step-width parameter was measured in an elderly population and preliminary data from patients with iNPH before and after shunt surgery were presented. Striton offers a new and reliable way of assessing step-width while walking without shoes or equipment attached to the feet. The method is applicable in healthy elderly and as part of clinical investigations of gait function in patients with iNPH.

4.1. Validation of step-width measurements
In the experimental pendulum setup, high linearity and accuracy of the step-width sensor were found, figure 6(a). This ensures that the sensors themselves, including the proposed model for linearization, are suitable to accurately detect distances in the interval relevant to the current application under static as well as
dynamic conditions. In this study, all EP and iNPH patients had step-widths in the interval 3.5 to 18 cm, ensuring that the chosen range of calibration was suitable.

The natural variation in step-width within subjects during single walks has previously been shown to be quite large, 4.3 times larger than that of step-length, and with a mean step-width SD of about 2.89 cm (Collins and Kuo 2013). Thus, the Striton test-retest and day-to-day variabilities were small compared to the expected step-width variability within a single walk. Our results showed no significant difference in neither test-retest nor day-to-day variability of a single person, confirming that sensor fixation and variation over time is not likely to significantly affect the assessment of mean step-width of a person.

To evaluate the function of the optical distance sensor against a Gold standard system during human walking, measurements in the frontal plane during leg passing were simultaneously performed using Striton and a 3D motion capture system, figure 6(b). Our results showed a high reliability when comparing Striton to a Gold standard system with a correlation coefficient of 0.98 and a maximum error of ±5.6% in the range 5–20 cm. This was comparable to the results of Trojaniello et al (2014a), who used the same type of sensor and slightly more than Bertuletti et al who used a time of flight type of sensor (Bertuletti et al 2017). The use of IMUs to measure absolute step-width is possible but the need for spatial calibration for each test person and fairly large uncertainty in the data suggests that this technique is needs further development to be used in clinic (Teuff et al 2019). The CI of the Bland–Altman plot comparing the step-width between Striton and the 3D motion capture system was even narrower for smaller step-widths (i.e. in the range of normal walking). This might be due to larger internal rotations between the systems when the subjects were asked to

Figure 8. (a) Step-width for all EP (mean ± SD), EP divided by sex (mean ± SD) and the four individual iNPH patients before and after surgery. * indicates significant difference, p < 0.001. (b) Step-width variability (CV %) for the same groups.
Figure 9. Linear regression of stride-time measurements with Striton and the instrumented walkway (n = 86, n strides = 711).

Figure 10. Bland–Altman plot comparing stride time measured by Striton and the instrumented walkway (n = 86).
Bias = −0.003 s. Dotted lines show 95% CI (±0.016 s).

walk with an un-natural wide-based gait pattern. Variations in the visual alignment of the reflective markers likely also resulted in small differences between the systems.

Preferably, step-width measured with Striton would also have been validated against the step-width parameter presented by the well-established instrumented walkway GaitRite®. However, since step-width data from GaitRite® are only retrieved during the stance phase of gait (Menz et al 2004) as opposed to the swing phase utilized with optical sensors, the two parameters are related but not straightforwardly comparable. Also, only normal walking was assessed with Striton on GaitRite® making the span for comparison small. Although there are large numerical differences due to different definitions of step-width, it is interesting, however, that differences in step-width previously seen between males (12.65 ± 1.81 cm) and females (9.99 ± 1.80 cm, p < 0.001) when assessed by an electronic walkway on 1390 elderly (Johansson et al 2016) were found also when assessed by Striton during the swing phase of gate.

The current placement of the Striton sensors, on the upper shanks, was chosen to increase the reliability of the step-width measurement. Due to the integrating process of the optical sensor the sampling frequency is only 26 Hz, thus, the longer measurement time attained by placing the sensors on the shanks as compared
to the feet is preferable to increase measurement accuracy. To further improve measurement reliability, a white curved plastic cover with good reflective properties serving as a target for the distance measurement was included in the Striton equipment. Placing the target on the outside of clothing also allows for measurement on persons with wide trousers reaching below the knees. Since this is common to hospital inpatients, this is an advantage for clinical gait assessment.

4.2. Validation of the stride-time algorithm
To validate the proposed new method of stride time measurements, mean stride time based on Striton was compared to that of the instrumented walkway using data from the EP. The Bland–Altman analysis showed a low bias of 0.003 s and a very narrow 95% CI of 0.016 s. Together with a very high and significant correlation ($R^2 = 1.00$) this confirmed that the stride time estimations, and thus step detection, were comparable between the systems. Previously, the maximum swing angular velocity has been used for gait phase detection, e.g. to aid in heel-strike and/or toe-off detection (Catalfamo et al 2010, Greene et al 2010, Lee and Park 2011, Gouwanda and Gopalai 2015), but to our knowledge never for stride time measurements. A limitation with this simple method is that it lacks the possibility to split the gait cycle into different phases, but for the purpose of step detection the peak angular velocity is easy and reliable to use.

4.3. Step-width in healthy elderly
Step-width is a well-known measure of dynamic stability, and an altered step-width variability is also an indication of reduced gait stability (Brach et al 2005, König et al 2016). An increased step-width is a common feature in, for example, many neurological disorders, and as such, clinical evaluation and follow-up is valuable in diagnostic and rehabilitation management (Brach et al 2005). In this cohort during walking at self-selected normal pace, the EP mean step-width was 5.22 cm with a SD of ±0.89 cm. Thus, for normal gait, the variation between healthy individuals is not very large. This possibly makes it easier to detect a disturbed dynamic stability outside of the normal range related to different disorders.

There was a significant difference in step-width between males and females, while the step-width variability was equal between sexes; see figures 8(a) and (b). The same findings have previously been seen when step-width was assessed on an instrumented walkway (Johansson et al 2016).

4.4. Step-width in patients with iNPH
An altered step-width and/or step-width variability is concluded to be a negative predictor of impaired gait in patients with neurological disorders, which makes step-width an important parameter to investigate when analyzing gait (Brach et al 2005, Galna et al 2013, König et al 2016). In our small sample of patients with iNPH, mean step-width was found to be 5.22 cm in the EP and 6.88 cm, confirming previous findings of a larger step-width in iNPH patients than in healthy elderly (Stolze et al 2000, Allali et al 2013). A reduction in step-width variability has previously been seen in patients with iNPH compared to healthy controls (Stolze et al 2000), and a similar reduction was found in Parkinson’s disease when step-width was measured using footswitches, an instrumented walkway and optical motion capture systems (König et al 2016).

After shunt surgery, step-width and variability improved (i.e. approached the levels of EP) in three out of four patients, strengthening our believes that an altered step-width is a reversible parameter which is valuable to measure quantitatively during preoperative investigation and following treatment. In one case (patient 3 in figure 8) the step-width increased after surgery. This patient walked with very short, shuffling steps before surgery and was substantially improved afterwards. Thus, an improvement is not always associated with a reduced step-width, and initial conditions must also be considered in the overall clinical assessment.

Despite its simplicity, Striton has the potential to assess several of the features that have been reported as important for the quality of gait (Hausdorff 2007, Rennie et al 2018). Next step will be to evaluate the clinical relevance of the step-width parameters in a larger study on patients with iNPH.

5. Conclusion
We conclude that Striton is a valid, reliable and wearable equipment for quantitative gait analysis including step-width assessment. This user-friendly and simple tool has the potential to advance clinical assessment of gait deficits in neurological diseases, with emphasis on pathologies affecting the base of support during walking.

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