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Single sensor measurement of heel-height during the push-off phase of gait

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Abstract

Objective. In healthy gait a forceful push-off is needed to get an efficient leg swing and propulsion, and a high heel lift makes a forceful push-off possible. The power of the push-off is decreased with increased age and in persons with impaired balance and gait. The aim of this study was to evaluate whether a wearable equipment (Striton) and algorithms to estimate vertical heel-height during gait from a single optical distance sensor is reliable and feasible for clinical applications. *Approach*. To assess heel-height with the Striton system an optical distance sensor was used to measure the distance to the floor along the shank. An algorithm was created to transform this measure to a vertical distance. The heel-height was validated in an experimental setup, against a 3D motion capture system (MCS), and test-retest and day-to-day tests were performed on 10 elderly persons. As a reference material 83 elderly persons were included, and heel-height was measured before and after surgery in four patients with the neurological disorder idiopathic normal pressure hydrocephalus (iNPH). *Main results*. In the experimental setup the accuracy was high with a maximum error of 2% at all distances, target colours and inclination angles, and the correlation to the MCS was $R = 0.94$. Test-retest and day-to-day tests were equal within ± 1.2 cm. Mean heel-height of the elderly persons was 16.5 ± 0.6 cm and in the patients with iNPH heel-height was increased from 11.2 cm at baseline to 15.3 cm after surgery. *Significance*. Striton can reliably measure heel-height during gait, with low test-retest and day-to-day variability. The system was easy to attach, and simple to use, which makes it suitable for clinical applications.

1. Introduction

The ability to walk is essential for all humans, and impairment of gait is often a constraint in daily life. Many diseases affect the motor and balance systems and finding the characteristics of the impairment in balance and gait may help to obtain the correct diagnosis (Fasano and Bloem 2013, Pirker and Katzenschlager 2016). A well-functioning push-off at the end of the stance phase is important for normal gait, since it is the main source of power for the ipsilateral leg swing and the forward acceleration of the centre of mass and thereby produce propulsion (Zelik and Adamczyk 2016). Most of the power during push-off is generated by the plantar flexor muscles and this power increases with increased cadence (Winter 1983). A longer stride tilts the shank more forward at the end of the stance phase, thus directing the power from the push-off to more propelling motion and a higher acceleration of the swing. A longer stride also increases the peak heel lift from the floor, here defined as heel-height. This indicates that the vertical heel-height can be an indirect measure of the push-off efficiency. With increased age the gait pattern is adapted in order to avoid imbalances, with e.g. reduced speed, weaker push-off and more flat footfall (Winter *et al* 1990, Rumble *et al* 2018). Such change of pattern is further reinforced in case of gait impairment.

Impaired gait is a typical symptom in patients with the neurological disorder idiopathic normal pressure hydrocephalus (iNPH). The mean age for onset of iNPH is about 70 years (Malm and Eklund 2006). The gait pattern is described as slow, broad based, shuffling and short-stepped (Stolze *et al* 2001, Relkin *et al* 2005), and

Stolze *et al* has shown that the foot clearance is lower and the footfall more flat for persons with iNPH compared with healthy controls (Stolze *et al* 2000). Today, when these patients are clinically assessed for finding the correct diagnosis or assessing improvement following treatment, the ability to lift the foot during gait is commonly visually judged by a physiotherapist and graded as adequate or not (Tinetti 1986). This is a coarse and subjective estimate where small changes are difficult to detect. Such a rudimentary measure of heel-height is also difficult to relate to other possible changes in the gait pattern, e.g. a changing stride length or leg swing acceleration/ velocity. Thus, a quantitatively measured heel-height parameter has the potential to contribute to a more comprehensive picture of the gait pattern, in healthy as well as in pathological gait. On the contrary, in scientific research advanced instruments such as treadmills, 3D kinematic systems or instrumented walkways are used to gain a detailed picture of the foot trajectory during gait (Winter 1992). Since most of these advanced instruments are expensive, require large, specialized laboratories and specially trained personal, they are seldom suitable for daily clinical investigations. In addition, they often result in complex data outputs that need specially trained personnel to be analysed.

Wearable sensors, based on inertial measurement units (IMU), have been suggested to be useful for assessing the quality of gait in everyday clinic due to their relative simplicity and low price (Trojaniello *et al* 2014, Anwary *et al* 2018). Sensor fusion techniques of IMU data are used to obtain e.g. spatial information (Madgwick *et al* 2011, Rouhani *et al* 2011), such as estimation of foot clearance and foot trajectory (Mariani *et al* 2012, Kitagawa and Ogihara 2016, Hannink *et al* 2017, Hori *et al* 2020). Major drawbacks with IMUs, however, are the need of thorough and time-consuming calibration every time used, and that due to problems with drift, a reset of the velocity is often needed for every step to obtain reliable spatial parameters. To comply with the healthcare's need for time-efficient, and disease-specific measurement instruments, we have developed a wearable system in which an optical measurement technique for the assessment of heel-height is combined with an IMU unit for gait analysis.

The aim of this study was to evaluate a wearable equipment and algorithms to estimate vertical heel-height during gait using an optical distance sensor, and to validate it in an experimental setup, against a motion capture system (MCS) and through test-retest and day-to-day trials on elderly persons. The hypothesis was that it is possible to measure heel-height, using a shank mounted optical distance sensor, during the push-off phase of gait with a senor module applicable in clinical practice.

2. Material and method

2.1. The in-house developed system

The in-house developed system, Striton (figure 1), previously described in Bäcklund *et al* (2020) was adjusted to include heel-height measurements by adding an infra-red triangulating optical distance sensor (Sharp GP2Y0A02YK0F, Sharp Inc., Japan) (figure 1(a)). The optical sensor has a measurement range of 20–150 cm, and an analog output signal with an internal update frequency of 26 Hz which was sampled with 256 Hz as the rest of the sensors in the system.

To maximize the precision, calibration was performed at regular intervals of 5.0 cm from 20 to 80 cm using the table of a milling machine equipped with a scale with 0.005 mm resolution (Sony, Magnescale LH10, Japan) as reference (figure 2). The range 20–80 cm was chosen to optimize the measurement range as found in human gait (healthy and abnormal). During calibration, the sensor was facing a white target (figure 1(b)). Curve fitting was applied for linearization, resulting in a 4th order polynomial:

$$\text{Distance[cm]} = 11.812x^4 - 91.055x^3 + 264.33x^2 - 361.29x + 232.68,$$

x = measured voltage from sensor [V], $R^2 = 1.00$.

The sensor system was uniformly placed on each subject. The optical distance sensor was placed on the lateral side of the upper part of the right shank pointing downwards aiming over the lateral malleolus (figure 1(b)) and the white reflective sheet (for step width measurement) was placed as high as possible without interfering with the knee joint. All alignments were done merely with eyesight. Measurements were started and stopped with a remote control. Data were stored on a micro-SD memory card and post-processed on a computer using a program developed in the software LabVIEW (LabVIEW 12.0 National Instruments, Austin, TX, USA). Before analysis, the heel-height signal was filtered using a 4th order, 10 Hz Butterworth low-pass filter. To detect the peak heel-height, the built in LabVIEW peak detector based on an algorithm that fits a quadratic polynomial to sequential groups of data points was used. To remove the offset of the measured heel-hight rendered by the placement of the sensor on the upper part of the shank, the mean of the first 100 samples during quiet standing was subtracted from the following distance readings.
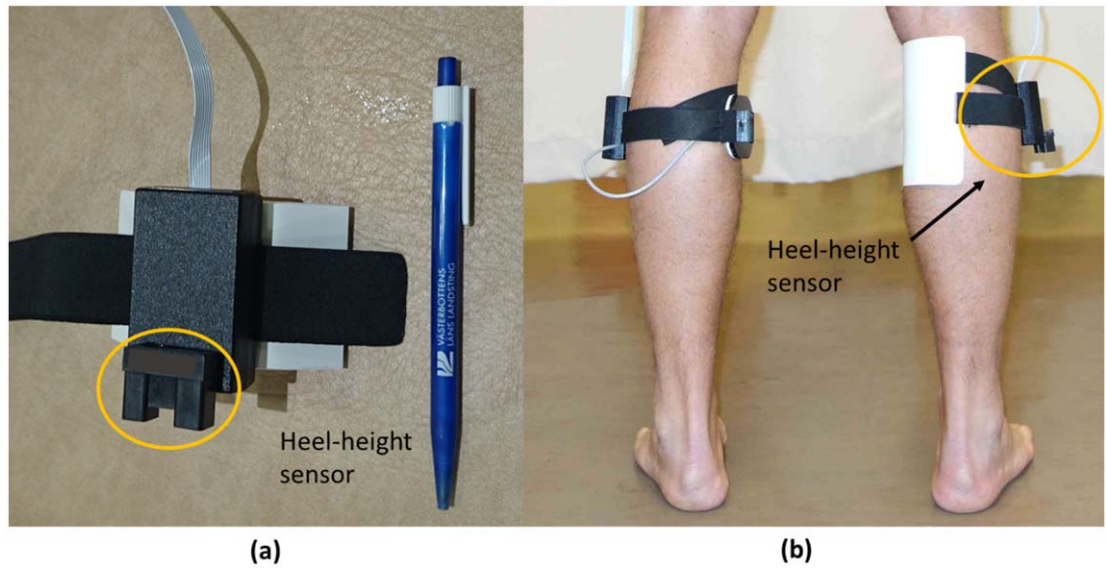
Figure 1. (a) Striton system with the optical heel-height sensor encircled. (b) Striton system including an IMU with the optical heel-height sensor placed on the right leg and an IMU with a step-width sensor on the left leg.
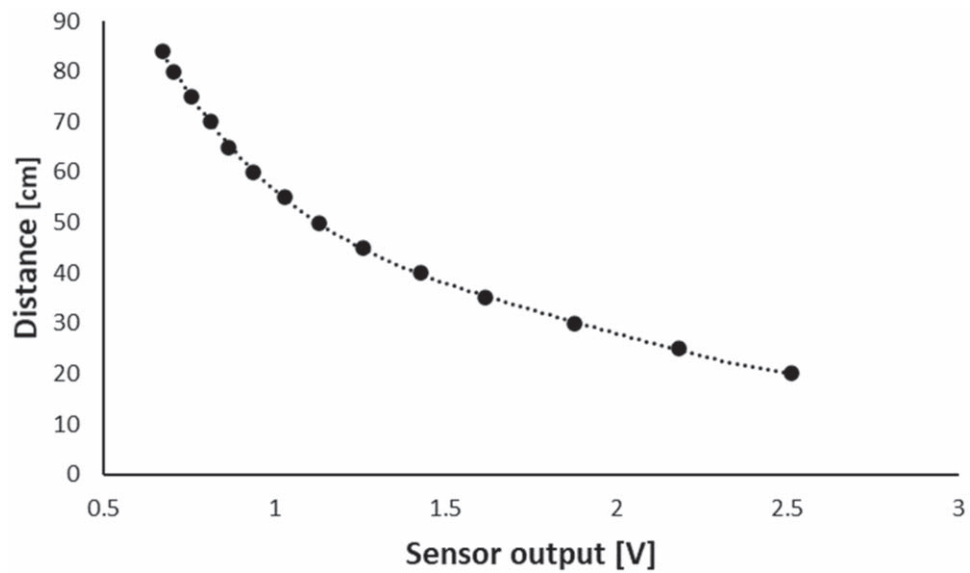

Figure 2. Calibration of the heel-height sensor. The dotted line is the fitted curve.

2.2. Calculation of vertical heel-height

The optical heel-height sensor of the Striton system continuously measures the distance from the mid of the heel to the floor in the direction of the shank (h_m) figure 3(b). The peaks of h_m are detected and used as maximum heel-height. During analysis, the positive peak values of the h_m trajectory are identified, since they correspond to the maximum heel-heights, and converted into vertical heel-heights. To convert h_m into vertical distance between the heel and the ground (h_v), an algorithm based on foot length (shoe size) was developed. Assumptions made were; 90° angle between the foot blade and the shank at toe off, $\alpha = \alpha_1 = \alpha_2$ due to triangular equality (figures 3(a), (b)), and toe clearance equal to 1 cm at the highest point (figure 3(b)) (Winter *et al* 1990). h_m and h_v could then be expressed as:

$$h_m = \sin \alpha * l / \cos \alpha, \tag{1}$$

$$h_v = \sin \alpha * l, \tag{2}$$

where l is the distance from the lateral malleolus to the toe (MT) + 1 cm toe clearance. Equations (1) and (2) give the vertical heel-height h_v as:
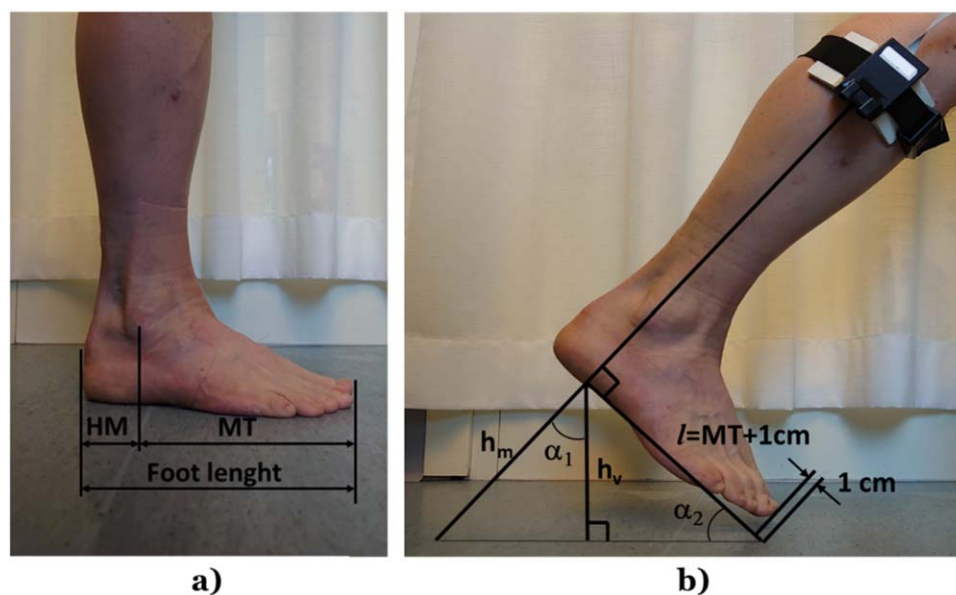
Figure 3. (a) Definition of the measures on the foot. Heel to lateral malleolus (HM) and lateral malleolus to the toe (MT). (b) For the conversion from measured distance (h_m) to vertical heel-height (h_v), h_m and l were used in equation (3).

Table 1. Shoe size to foot length conversion.

EU shoe size	35	36	37	38	39	40	41	42	43	44	45
Foot length [cm]	21.0	22.0	22.6	23.3	24.0	24.6	25.3	26.0	26.6	27.3	28.0

$$h_v = \sin\left(\arctan\left(\frac{h_m}{l}\right)\right) * l, \tag{3}$$

In figure 3, the anthropometry of the foot is shown. The distance between heel and lateral malleolus (HM) was defined as 0.18^* foot length (Hajaghazadeh *et al* 2018). MT was based on shoe size which was converted into the corresponding foot length according to the international standard 'ISO 9407:2019 shoe sizes—Mondopoint system' (table 1).

2.3. Validation against gold-standard system
A MCS (Oqus®, Qualisys AB, Gothenburg, Sweden) was used as gold standard to validate the Striton heel-height measurement during gait. The system was based on eight optical cameras with a sampling frequency of 60 Hz. Three reflective markers were placed on the right leg: one on the lateral knee joint space, one on the lateral malleolus and one on the 5th metatarsal joint (figure 4). The markers were identified using QTM's software and were then exported to the software Visual3D (C-Motion Inc., Maryland, USA) for post-processing. The shank's long axis was defined as the line between the lateral knee joint marker and the marker on the lateral malleolus. The vertical line from the floor to the point of intersection between the long axis and the line parallel to the floor passing through the 5th metatarsal was used to assess heel-height (figure 4).

2.4. Participants
In this study three groups were included. The first group consisted of ten healthy individuals (HI, 33.8 ± 8.2 years, 5 females) that participated in the validation of Striton versus the MCS. The second group consisted of 83 elderly persons (EP, 70 years old, 49 females) used as a reference group of elderly persons, and from these 10 were randomly recruited for the evaluation of test-retest and day-to-day variability, (70 years old, six females). The EP were consecutively recruited as part of a larger study (Healthy Aging Initiative at Umeå University, Sweden, www.healthyageinginitiative.com) to which every community dwelling person is invited upon turning 70 years old. Initially, 100 persons were recruited. Exclusion criteria were all known conditions with potential impact on gait performance (Parkinson's disease ($n = 1$), stroke ($n = 8$), arthrosis in knee ($n = 1$), pain when walking ($n = 3$) and corrupt step-height data ($n=5$)). The third group consisted of four patients with diagnosed iNPH (73
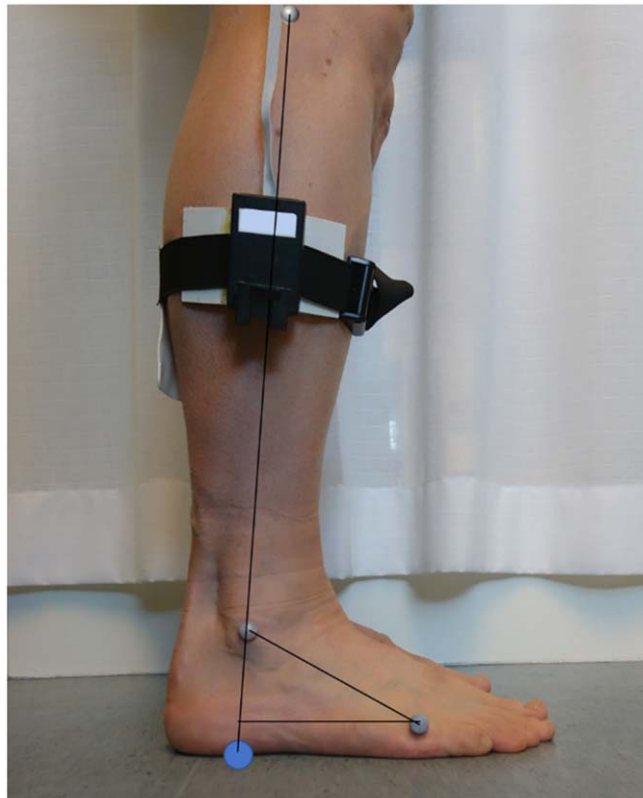
Figure 4. Placement of the three reflective markers for validation against the motion capture system (MCS). Markers were placed at the knee joint, the right lateral malleolus and at the fifth metatarsal joint. The blue dot represents the point on the heel, defined from three reflective markers, that was used to assess heel-height with the MCS.

±3.2 years, three females). In this group, pilot measurements of heel-height and heel-height variability as part of pre- and post-CSF shunt operative clinical evaluations by a physiotherapist were performed.

All participants gave their informed written consent to participate in the study, which was approved by the Regional Ethical Review Board in Umeå (Dnr 09-120M/214-160-32M**/** 2014-246-32M/2018-155-31M).

2.5. Experimental setup
An experimental setup was constructed of a flat, angled surface where targets of different colours were placed (figure 5). The distance between the target and sensor was measured with a measuring tape and the six targets were white, grey (three different tones with different reflectivity), blurry blue and green respectively to mimic common floor mats (figure 6).

2.6. Test protocols
All tests in protocol two to four (see below) were performed barefoot with the Striton system mounted as shown in (figure 1(b)). When the recording started the person initially stood in quiet stance for one second to get an initial reading of the distance from the sensor to the floor and was then told to walk along a hypothetic straight line towards a target.

Protocol 1: Validation in experimental setup

Measurements were performed on six targets in different colours and at seven different inclination angles from 90° to 30° in steps of 10° (figure 6) and (table 2).

Protocol 2: Validation against 3D MCS

Three reflective markers were placed on the HI according to (figures 1 and 4). Each HI walked approximately 4 m (the maximum sampling volume of the MCS) in total 40 times; 10 times with self-selected, 10 with slow, 10 with fast, and 10 times with self-selected speed at increased step-width. For Striton, heel-height was defined as the highest vertical position for each right stride. For the MCS, it was defined as the maximum lift of the heel (based on three reflective markers, see (figure 4)) in the sagittal plane for each stride.

Protocol 3: Test-retest and day-to-day variability

To test whether the sensor placement or daily variations in gait pattern for individual persons had a considerable impact on the heel-height measurement, test-retest and day-to-day measurements were
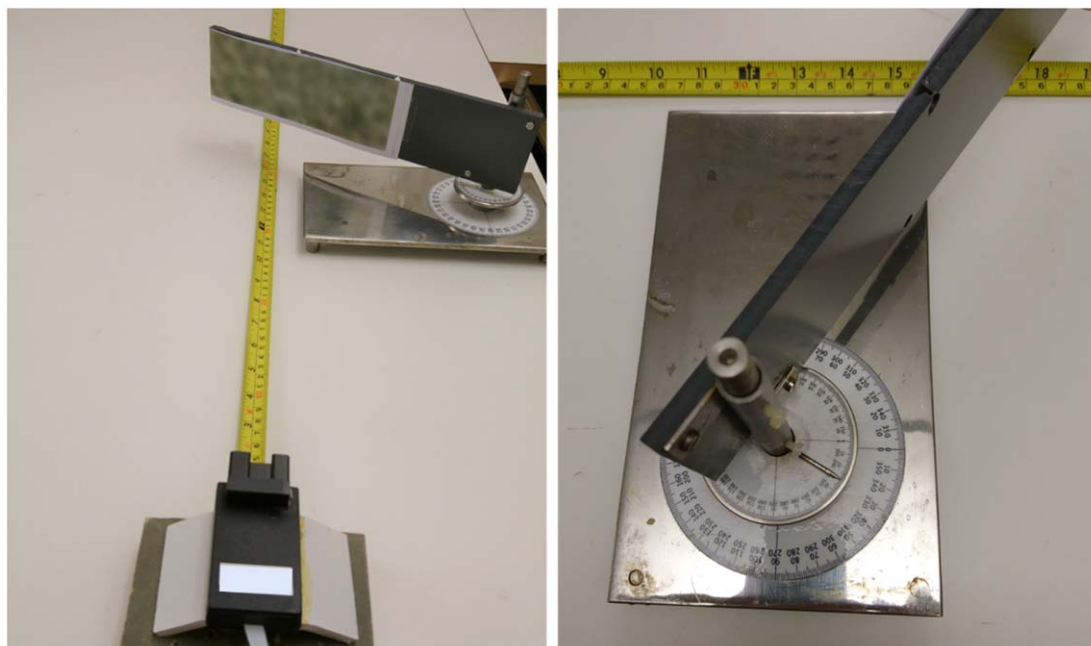
Figure 5. Experimental setup for evaluation of different target colours and measurement angles.
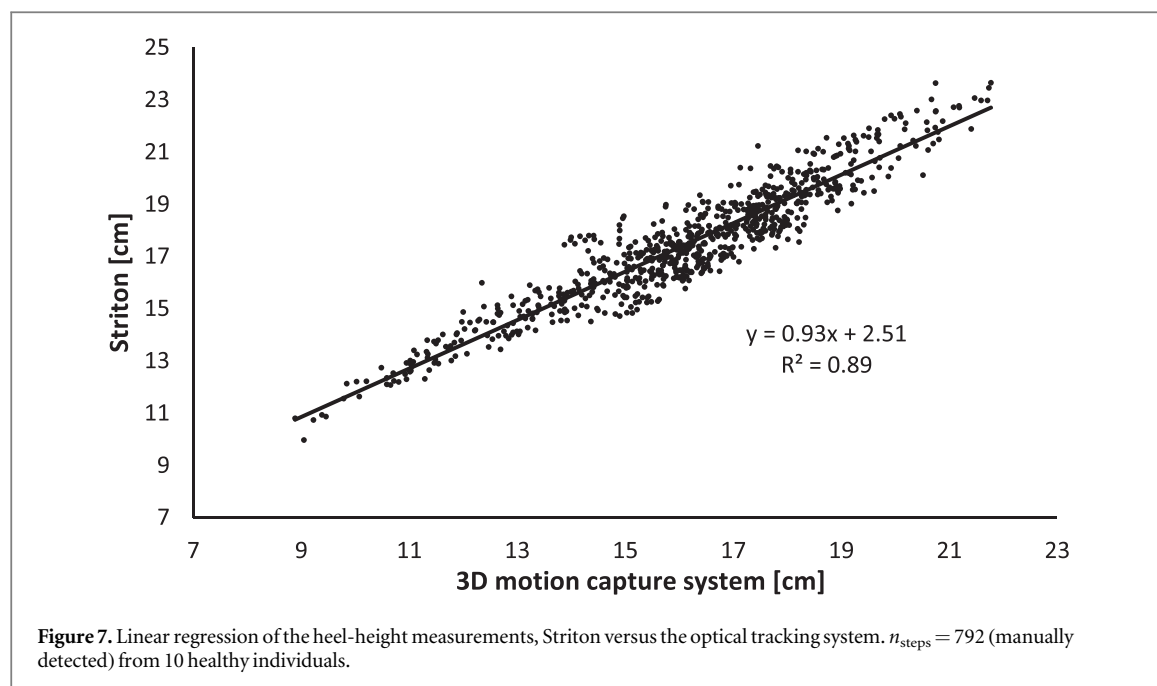

Figure 6. The six surface colours used. From the left; white, light grey, medium grey, dark grey, blurry blue and blurry green. The blurry surfaces simulate the colouring of common floor mats.

Table 2. Static measurement of mean absolute error (MAE%) in distance when starting from 30 cm at 90° inclination angle and therefrom decreasing the angle to 30° in steps of 10°. The MAE% is presented for all the different surfaces and angles. At the start of each measurement at 90° distance was set to zero.

Angle [°]	Distance [cm]	Mean absolute error in %					
		White	Light grey	Medium grey	Dark grey	Blurry blue	Blurry green
90	30	0	0	0	0	0	0
80	32.2	0.6	1.2	0.6	0.6	1.7	0.9
70	34.6	0.6	0.7	0.1	1.0	0.1	0.2
60	36.8	0.4	1.2	0.3	1.6	1.5	0.4
50	40.1	0.8	1.3	0.8	0.5	1.5	0.3
40	43.9	0.2	0.7	0.9	2.6	0.2	0.5
30	50.2	0.7	2.0	3.6	5.2	1.8	2

performed. The test-retest measurements were separated by two hours and the day-to-day measurements by one week. Between sessions the system was completely removed from the test person. The EPs were instructed to walk at their normal walking pace for 20 m two times on both occasions. The measurements were always performed by the same operator.

Protocol 4: Reference material and patients with iNPH.

Figure 7. Linear regression of the heel-height measurements, Striton versus the optical tracking system. $n_{steps} = 792$ (manually detected) from 10 healthy individuals.

All EPs ($n = 83$) and patients with iNPH ($n = 4$) walked 20 m in a straight corridor two times. Both trials were performed at their normal and self-selected speed.

2.7. Statistics

For comparison between Striton and the MCS, Pearson correlations and Bland–Altman plots were used. The analyses of test-retest and day-to-day variation were performed according to Lakens (2017) using two one-sided depended samples t-tests for equivalence (TOST, Excel script (https://osf.io/q253c/)). In the TOST test, upper (Δ_U) and lower (Δ_L) equivalence bounds were specified based on the values accepted as clinically equal between tests. Here, Δ_U and Δ_L were chosen to ± 1.2 cm (Lakens 2017). In the comparison between males and females for heel-height in the EP, a students two-sided t-test was used. For all tests, $\alpha = 0.05$ was required for statistical significance. The mean absolute error in percent ($MAE_\%$) was calculated as: $MAE_\% = ABS((m_d - d/d) * 100)$, where m_d was the mean of the measured distance and d the actual distance in the experimental setup. Variability in heel-height was reported as coefficient of variation (CV) calculated as within-subject SD divided by within-subject mean.

3. Results
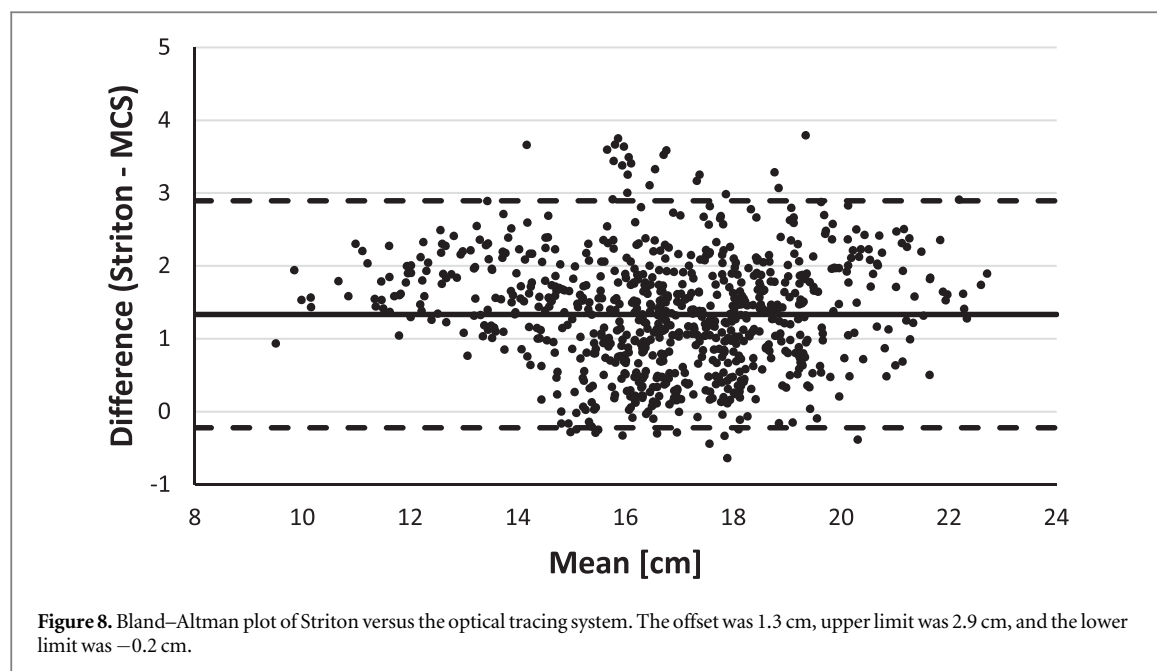
3.1. Validation in experimental setup

In table 2 the $MAE_\%$ for all measurements is presented. For all surfaces except medium and dark grey the $MAE_\%$ was less than 2% at all distances and angles. The medium grey surface, with less reflective properties, had a maximum $MAE_\%$ of 3.6% at 30°, and the dark grey had maximum $MAE_\%$ of 2.6% and 5.2% at 40° and 30°, respectively.

3.2. Validation against 3D MCS

The heel-height from Striton and the MCS in the group of 10 HI had a correlation of $R = 0.94$ ($p < 0.001$) and a slope of 0.93 (figure 7). The Bland–Altman plot showed that the Striton system overestimated the heel-height by a mean of 1.3 cm, and the 95% confidence interval was ± 1.55 cm. The difference between the systems was not dependent on mean heel-height (figure 8).

3.3. Test-retest and day-to-day variability

The test-retest of heel-height in the subgroup of 10 HE showed a mean difference of 0.4 ± 1.5 cm (mean $\pm$ standard deviation (SD). Baseline: 15.8 ± 2.1 cm, $n_{steps} = 639$, after two hours: 16.2 ± 2.4 cm, $n_{steps} = 610$). The corresponding day-to-day mean difference was 0.2 ± 1.7 cm (baseline: 15.8 ± 2.1 cm, $n_{steps} = 639$, after one week: 16.0 ± 2.7 cm, $n_{steps} = 591$). Both test-retest and day-to-day measurements were found to be equal within ± 1.2 cm according to Lakens TOST equality test ($p < 0.05$). There was no significant difference in walking speed or numbers of steps between the test occasions.

Figure 8. Bland–Altman plot of Striton versus the optical tracing system. The offset was 1.3 cm, upper limit was 2.9 cm, and the lower limit was −0.2 cm.

3.4. Heel-hight in EP and in patients with iNPH

Compared to the EP the patients with iNPH had lower heel-height and a higher heel-height variability before surgery. After surgery, the heel-height increased, and the variability decreased. Before surgery, heel-height of the four patients varied between 7.5 and 15 cm and after surgery the heel-height increased by a mean of 4.1 cm (figure 9(a)). The heel-height variability varied between CV = 7.7 and 22.2% with a mean of 12.3 before surgery and decreased to a mean of 4.8 after surgery (figure 9(b)). All patients were reported as clinically improved after surgery. Mean heel-height for all EPs was 16.7 ± 0.6 cm and males had higher heel-height than females (17.5 ± 0.62 and 16.2 ± 0.58 cm respectively, $p < 0.001$). Mean heel-height variability was CV=3.3% with no difference between males and females. The physiotherapist found the system was easy to attach to the patients and the total measurement time was about 5 min.
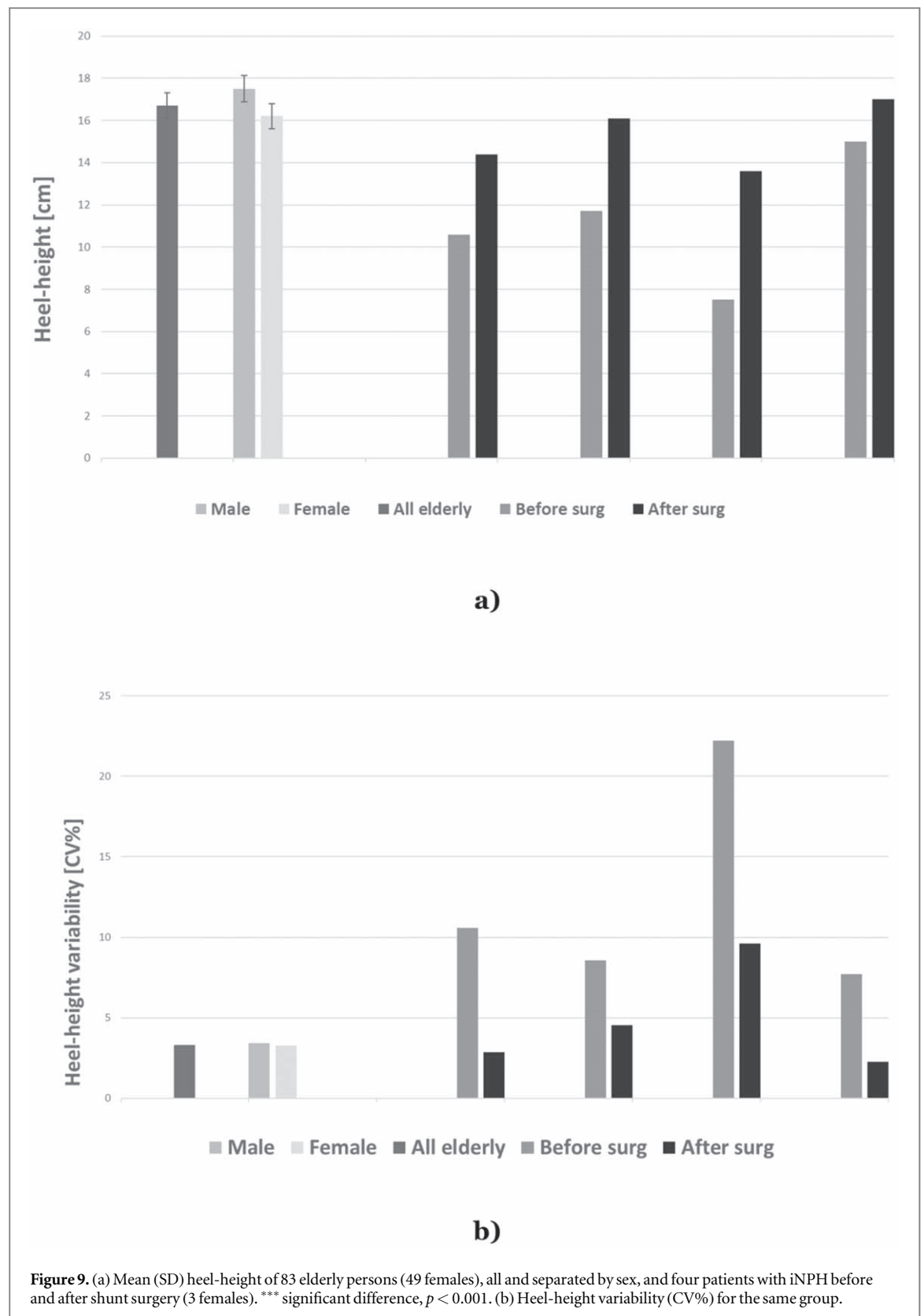
4. Discussion

In this paper, a single optical sensor was implemented in a novel in-house built wearable gait analysis system, for measurement of heel-height during the push-off phase of gait. Validations were made in an experimental setup, against an MCS, and by attaining a reference material and performing test-retest and day-to-day measurements on healthy elderly. The feasibility in everyday clinic was also assessed through measurements on four patients with the neurological disease iNPH. The results from the validation show that Striton, including an optical distance sensor, give reliable heel-height measurements that are repeatable between occasions. The difference in heel-height and heel-height variability between healthy elderly and patients with iNPH, as well as improvement after surgery, also makes it a promising parameter to explore further in the gait assessment of iNPH patients.

4.1. Validation in experimental setup

The angles of incidence and distances to the floor during normal gait was simulated in an experimental setup, as the angle became narrower the distance increased which mimics the situation during gait (figure 5). Angles of incidence during gait were estimated from the MCS measurements on the HI, and here the shank's angle of incidence against the floor was never below 45°. In our setup, the angles of incidence ranged between 90° and 30° (table 2), and the only angles of incidence resulting in MAE% above 2% were the two dark grey surfaces at 30° and only the darkest grey at 40°. This indicates that the sensor measurements will be accurate on all surfaces and at all relevant angles. Similar tests were performed by (Bertuletti *et al* 2017) who used time-of-flight sensors in a step-width application, and in their work MAE% were in the same range as in this study (Bertuletti *et al* 2017).

4.2. Validation against 3D MCS

The agreement between Striton and the MCS in heel-height estimation was very good, with a linear regression coefficient $R^2 = 0.89$, an offset of 1.3 cm and a 95% CI of ± 1.55 cm (figures 7 and 8). To estimate vertical heel-height from the optical sensor, which measures distance in the direction of the shank, certain assumptions had

Figure 9. (a) Mean (SD) heel-height of 83 elderly persons (49 females), all and separated by sex, and four patients with iNPH before and after shunt surgery (3 females). *** significant difference, $p < 0.001$. (b) Heel-height variability (CV%) for the same group.

to be made that likely influenced the discrepancy between the systems. The foot-shank angle was assumed to be 90° at the peak height of the heel. To evaluate the potential effect of this assumption, small deviations in foot-shank angle were applied; a 5° angle increase gave only about 4 mm lower heel-height when applied to the shoe size 42. Toe clearance during normal walking was set to a constant of 1 cm. This assumption was based on a study by Winter *et al* who showed that this holds for both young and elderly when walking at normal self-selected speed (Winter *et al* 1990). Toe clearance variability has been shown to increase with age (Barrett *et al* 2010), but gait speed does not have a significant impact on the minimum height (11, 14 and 17 mm at slow, normal and fast

speed respectively) (Mariani *et al* 2012). Thus, the choice of 1 cm is reasonable. Also, the length of the foot was estimated from the shoe size instead of being measured. This was a deliberate choice, since in the clinical situation it is simpler and more time-efficient to ask for the individual's shoe size than to measure the length of the foot. The difference in length between a shoe of a certain size and the actual foot may differ up to about half a shoe size (± 3 mm), resulting in errors in the vertical heel-height estimation. However, inserting ± 1 shoe size in our model only results in a heel-height difference of ± 3 mm, which is likely to be clinically irrelevant.

Despite some intra- and interindividual variation in these parameters the correlation between the systems was high, supporting the validity of the vertical heel-height model. The small discrepancy that remains is also of minor importance in the clinical setting since the only comparison that will be made is repeatedly on the same person, e.g. before and after some intervention, or to other groups investigated with the same equipment.

4.3. Test-retest and day-to-day variability

All repeated measurements of test-retest and day-to-day variability in the subgroup of 10 EP were equal within ± 1.2 cm. Given that the heel-height on average increased with 4.1 cm in the iNPH patient's post-surgery, a resolution of 1.2 cm is promising from a clinical perspective. The instruction was to walk at your normal speed for 20 m along a hypothetical straight line in a corridor, and since there was no control of speed or walking pattern there is no guarantee that these were the same on all occasions. There was, however, no differences in speed on average between the occasions.

4.4. Heel-height in EP and patients pre- and postoperatively

Measurements in the EP group gave age-matched reference levels of the heel-height parameter when assessed with the Striton system. Mean heel-height was 16.5 cm for the EP group, with a significantly higher value for males, figure 9. This difference between sexes was probably due to the smaller foot size of women; in the north American and European populations the mean difference in foot length between males and females is about 2.5 cm (Jurca *et al* 2019).

For all four iNPH patients the heel-height increased, and the heel-height variability decreased after surgery and approached the reference levels of the EP group (figures 9(a) and (b)). All patients were reported to be clinically improved after surgery, and since the symptoms in balance and gait are the ones that often improve the most (Fasano *et al* 2020), it is promising that the objective measurement of heel-height and heel-height variability may be good indicators of clinical outcome in this domain. A better balance post-surgery has the potential to increase the power in the push-off phase, resulting in an increased heel-height which was seen in this study.

5. Conclusion

Striton can reliably measure heel-height during gait, with low test-retest and day-to-day variability and high agreement with the gold standard 3D MCS commonly used to track foot trajectory in the laboratory setting. The system is reliable regardless of inclination angle of the lower leg during walking, and applicable on most kinds of floor surfaces. The system is also easy to attach, and simple to use, which makes it suitable for clinical applications. Even though the clinical relevance of the heel-height parameter needs further research, the results are promising as Striton could successfully measure gait improvements in a sample of patients treated for iNPH.

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