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AGREEMENT IN GAIT SPEED FROM SMARTPHONE AND STOPWATCH FOR FIVE METER WALK IN LABORATORY AND CLINICAL ENVIRONMENTS

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Abstract

Gait speed is suggested as an independent predictor of post-operative morbidity and mortality in elderly cardiovascular disease (CVD) patients. Society of thoracic surgeons has recently classified gait speed as the only important indicator of health for CVD patients. It has been seen that patients with slow gait speed above 70 years of age, taking more than 6 seconds to walk 5 meters are particularly at high risk for adverse outcomes. Twelve young participants walked in their self-selected, slow and fast speed with five reflective markers at sternum and heels and toes of both feet in laboratory environment. A smartphone was affixed at the pelvis using a smartphone holster. Simultaneously, an examiner used stopwatch to record the elapsed time necessary to cross 5 meter distance. Smartphone based app also computed gait speed. Intra-class correlation coefficients comparing velocities from camera system, smartphone and stopwatch systems were found to be highly reliable (ICC (3,k)=0.82) for slow walking speed. Similarly, fairly good reliability were found for fast (ICC(3,k)=0.70) and normal walking speed (ICC(3,k)=0.66). Five CVD patients were tested in clinical environment with smartphone and its feasibility was assessed for gait speed. This study shows that the smartphone and stopwatch gait speed methods have clinically acceptable agreement for the measurement of gait velocity in the two different environments. The smartphone based reliable measurements could help patients on their own to assess operative risks and health during perioperative period.

Keywords

Inertial Sensors; Cardiovascular Disease CVD; gait speed

INTRODUCTION

In the year 2010, 35% (223 patients) of adult cardiac surgeries were performed on patients 70 years of age and older at Carilion Roanoke Memorial Hospital (CRMH). Considering mortality at old age, it is observed that patient age is an independent risk factor for postoperative complications including major morbidity and death [1]. With aging there is decline in physical functioning [2, 3], and this leads to higher rates of disability, institutionalization and mortality [4–6]. Clinical researchers have suggested that there is significant need for a more accurate prediction of surgical risk in elderly patients considering cardiac surgery [7]. Frailty has been investigated as a predictor of disability and adverse outcomes in older adults, and it has recently been investigated as a risk factor for patients undergoing cardiac surgery [7].

Gait speed, as a clinical indicator of frailty, has been identified as the strongest predictor of mortality in individuals with coronary artery disease [8, 9]. Gait speed is a simple, but also a potential clinical indicator of functional status in older adults [10, 11] and is known to be associated with key health outcomes in elderly [12]. Gait speed is found to be associated with survival among older adults [13–17] with 12% higher mortality with every 0.1-m/s slower gait speed [10]. Some researchers have recommended gait speed as “sixth vital sign” from its ability to predict about one’s health status in future, with its ease of administration, grading, interpretation and minimal cost involved in its determination[18]. Studenski et. al. considered gait speed as a simple and accessible summary indicator of vitality which integrates disturbances in multiple organ systems such as heart, lungs, circulatory, nervous, and musculoskeletal systems which affect survival[10]. An objective gait speed measurement in clinical environments may refine survival estimates in frail cardiac patients because it is quite informative [19]. Afilalo et al. (2010) found that elderly patients who walked 5-meter and took more than 6 seconds were associated with a 2- to 3-fold increase in risk of major morbidity and mortality in post-cardiac surgery [20]. In addition, patients with slower gait speed were more likely to have longer lengths of stay in the hospital and did required discharge to a rehabilitation facility postoperatively [20, 21]. Although there being considerable variation in gait speed testing procedures including distance of walk [22]. Bohannon compared gait speed over 2.43 meters (8 feet) and 6.09 meters (20 feet) and found that it was feasible to measure gait speed in non-laboratory setting[23] for distance less than 20 feet with one step before and after the start and stop mark[23–25]. In the gait speed assessment protocol defined over short distances (such as 5 meter) there is an acceleration phase and a deceleration phase as part of gait speed [18, 26]. Inclusion of acceleration and deceleration phases in gait speed estimation is highly correlated to that with its exclusion in estimating gait speed. Inertial sensors have been found to be highly useful in finding temporal gait events of gait [27, 28].

Thus, there is a need to establish objective and reliable gait speed testing protocols in clinics. We hereby evaluated and established smartphone based technique of measuring gait speed which could feasibly be implemented as a routine measurement in outpatient clinics.

METHODS

Subjects

Twelve healthy young adults (6 males and 6 females) participated in laboratory study. The participants mean age was 28±4 years, height was 177±13 cm, and weight was 69±11 kg. All participants were healthy, independent and non-sedentary. Participants were formally screened for major musculoskeletal, cardiovascular, and neurological disorders by a research coordinator during initial participant contact. Exclusion criteria of this study were factors that could interfere with gait, such as medication use, presence of neuromuscular disease and, balance and vision disorders. Informed consent was approved by the Institutional Review Board (IRB) of Virginia Tech and Carilion Clinic IRB and was signed by all participants prior to the study.

Five cardiac patients were recruited from outpatient care in the cardiac department in Carilion Roanoke Memorial Hospital (CRMH) for feasibility portion of the study. After all patients had provided written consent and anthropometric data was collected, they had their vital signs performed by clinical nursing research staff (heart rate, blood pressure, etc.).

Equipment and data acquisition

Laboratory Data Collection—In the laboratory, the data acquisition was carried out using a smartphone (iPhone 5, Apple Inc. Cupertino, CA95014) based application. The smartphone was used to measure motion data from in-built accelerometer and gyroscope signals. Stopwatch was used by one of the experimenter to time when participants crossed start and finish line. A six-camera ProReflex system (Qualysis, Gothenburg, Sweden) was used to collect three-dimensional movement data of participants using passive infra-red markers (figure 1). A total of six reflective markers were attached on both heel, sacrum, sternum of the participants and start and finish mark of walking track. The camera frame rate was set to 120Hz. The marker positioned at sacrum was used to find the walking velocity. The data was processed using custom software written in MATLAB (MATLAB version 6.5.1, 2003, computer software, The MathWorks Inc., Natick, Massachusetts).

Participants—Twelve healthy participants participated in Locomotion Research Laboratory, Virginia Tech and were instructed to walk at three different speeds on the walking track: comfortable self-preferred pace [29], fast (or maximum) gait speed “as fast as safely possible”; and slower than normal walking speed. The walking track had a starting and finish mark five meters apart. Participants were instructed to stand still with their feet behind and just touching the starting line marked with grey duct tape and then to walk at their normal pace along a 5-m course until a step past the finish line after an audio signal was provided to start walking (at either fast, slow or normal speed). The app and motion capture data collection was started before providing the audio signal to the participants. Stopwatch timing started with the first footfall and stopped with participant’s first footfall after crossing the 5-m end line. Five walking trials were collected at all three walking speed using this protocol from each subject in laboratory.

Gait speed estimation using smartphone signals

Gait velocity is determined by computing the time taken to walk a specified distance (default as 5m) where

$$Gait\ Velocity = \frac{Distance\ walked}{Total\ Time} \quad (1)$$

To determine the start and stop events, the resultant acceleration is analyzed for distinct transition periods (figure 2)[27]. The resultant acceleration is computed over a window or 1 second using the following equation

$$A = \sqrt{{a_x}^2 + {a_y}^2 + {a_z}^2} \quad (2)$$

where a_x, a_y, and a_z are the components of acceleration

The acceleration signal is analyzed in one second blocks during the initial standing period to determine the activation threshold. This threshold is calculated using the variance of the resultant acceleration blocks for the initial standing period. Nominally, this threshold has been calculated using the mean plus two standard deviations of the variance recorded during the first 5 seconds of standing prior to walking. The start time is then defined as the time at which the variance of the resultant acceleration exceeds the threshold value. The stop time is similarly defined as the time at which the variance of the acceleration drops below the threshold. The start and stop events are illustrated in Figure 1.

Clinical Data Collection—To determine the feasibility of measuring gait speed in clinics using smartphone, we recruited a separate convenience sample of five patients, receiving outpatient care in the cardiac department in CMRH for feasibility portion of the study. The participants mean age was 76.8±6 years, height was 175.2±12.2 cm, and weight was 81.2±11 kg. The participants consisted of three females and two males. After all subjects had provided written consent and had their vital signs performed by clinical research staff (heart rate, blood pressure, etc.). The demographics of the subjects were collected. Then subjects were approached by clinical research staff and asked to perform 5 m walk at their normal walking pace. Light sensors were used to determine time taken by participants for crossing start and finish line in the clinic (figure 3). Subjects were verbally asked about their acceptability for smartphone at their waist. This feasibility study also involved training clinical research staff in using smartphone. The time to train clinical staff in using App, time to mount smartphone at appropriate position and time to administer subjects was also evaluated.

Statistical Analysis

All data analyses was done using MedCalc Statistical Software version 12.7.7 (MedCalc Software bvba, Ostend, Belgium; http://www.medcalc.org; 2013). Intra-class correlation ICC(3,k) for three measurement systems (same raters for all subjects): smartphone, stopwatch and motion capture was assessed for consistency and absolute agreement for all three kinds of walking speed. Consistency is important when systematic differences between raters are irrelevant and absolute agreement when systematic difference is relevant. Two intra-class correlation coefficients (ICC) models have been used to measure reliability. By assuming the three measurement systems as judges and considering them as fixed effects, the consistency of the three ratings obtained from the three systems is measured by ICC(3,k) [30]. ICCs were interpreted as Fleiss suggested: ICC>0.75 as excellent reliability, 0.4<ICC<0.75 as fair to good reliability and ICC<0.4 as poor reliability [31].

RESULTS

It was found that slow walking speed had excellent reliability (ICC=0.82) and fast (ICC=0.70) and normal walking (ICC=0.66) speed had good reliability as well. The absolute agreement reliability coefficient (measure of systematic errors in measurement systems) among three velocities was also found to be fairly good as seen in Table 1. It was also found that systematic difference for all three walking speed differed with the ground truth velocity as determined by camera system in laboratory (figure 5). This was evident when velocities were fitted through the regression line (figure 4).

It was evident from clinical feasibility experiment that velocity estimation using stopwatch was not found to be accurate when compared to the ground truth velocity (through light sensors) whereas smartphones always under-estimated the walking velocities in patients (figure 3 and figure 6).

DISCUSSION

Gait speed is a commonly used measure in health care research, particularly among preoperative cardiac patients [19, 21, 32]. Some studies have previously used inertial sensors in fall risk assessment in hemodialysis clinics [33, 34]. This study demonstrates how gait speed (related to major health related outcomes in frail population) can be measured feasibly using smartphone based methodology in clinical environments. There may be important losses of information when measurement of gait velocity is prone to human timing errors. Thus in clinical practice where gait speed is important predictive of severe health-outcomes such as mortality and a subsequent physical disability, an objective, accurate and reliable way is required for gait speed measurement. Five meter gait speed does not introduce fatigue in patients with cardiovascular impairment awaiting surgery[32]. Thus predictive validity of gait speed through an objective method of assessment could be used as a prescreening tool for many different kinds of surgical procedures and in turn help clinicians to identify cardiac patients who may need intensive rehab or preplan their longer stay in hospital with specialized nursing care before return to home.

Some limitations of current study need to be mentioned. Smartphone based assessments required participants to stand-still before and after 5-m walk. As automatic algorithms developed in smartphone app determined velocity by start and stop times of movement. If any other movement artifact is followed after or prior to the walking task, the movement time may get increased than the actual walking time and thus resulting in reporting of lower velocities by the app.

CONCLUSIONS

The accurate measure of gait speed can improve the clinical evaluation of cardiac patients, providing an earlier detection of individuals at higher risk of major health-related events such as physical disability and mortality. Our study demonstrated that 5-m gait speed measurement using smartphone is a reliable objective measure, however adhering to certain protocol is suggested for using smartphone app. Evidence of concurrent validity was demonstrated by showing associations with the speed measurement using stopwatch and motion capture system in laboratory environment and with light sensors in clinical environment. Five meter gait speed was easily implemented in cardiovascular clinical practice with high acceptability by the patients and clinical research staff. Participants started with standing still posture and walked at their usual pace, as if they were walking in their own home, and given no further encouragement or instructions. This data can be readily collected in non-laboratory environments and can be used to help interpret the results for health related events.

Although different methods have been used previously to measure gait speed and these have affected clinical interpretation and implementation of the gait speed [22, 35]. By providing a smartphone based clinically useful gait speed assessment method with a well-defined protocol which is simple, quick, easy to perform in clinics, it is hoped that smartphone for gait speed assessment will be promoted and encouraged in clinical and research settings.

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REFERENCES

[1]. Lee DH, Buth KJ, Martin BJ, Yip AM, and Hirsch GM, "Frail patients are at increased risk for mortality and prolonged institutional care after cardiac surgery," Circulation, vol. 121, pp. 973–8, 3 2 2010. [PubMed: 20159833]

[2]. Onder G, Penninx BW, Lapuerta P, Fried LP, Ostir GV, Guralnik JM, et al., "Change in physical performance over time in older women: the Women's Health and Aging Study," J Gerontol A Biol Sci Med Sci, vol. 57, pp. M289–93, 5 2002. [PubMed: 11983722]

[3]. Lindle RS, Metter EJ, Lynch NA, Fleg JL, Fozard JL, Tobin J, et al., "Age and gender comparisons of muscle strength in 654 women and men aged 20–93 yr," J Appl Physiol (1985), vol. 83, pp. 1581–7, 11 1997. [PubMed: 9375323]

[4]. Vasunilashorn S, Coppin AK, Patel KV, Lauretani F, Ferrucci L, Bandinelli S, et al., "Use of the Short Physical Performance Battery Score to predict loss of ability to walk 400 meters: analysis from the InCHIANTI study," J Gerontol A Biol Sci Med Sci, vol. 64, pp. 223–9, 2 2009. [PubMed: 19182232]

[5]. Guralnik JM, Ferrucci L, Pieper CF, Leveille SG, Markides KS, Ostir GV, et al., "Lower extremity function and subsequent disability: consistency across studies, predictive models, and value of gait speed alone compared with the short physical performance battery," J Gerontol A Biol Sci Med Sci, vol. 55, pp. M221–31, 4 2000. [PubMed: 10811152]

[6]. Guralnik JM, Ferrucci L, Simonsick EM, Salive ME, and Wallace RB, "Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability," N Engl J Med, vol. 332, pp. 556–61, 3 2 1995. [PubMed: 7838189]

[7]. Sundermann S, Dademasch A, Praetorius J, Kempfert J, Dewey T, Falk V, et al., "Comprehensive assessment of frailty for elderly high-risk patients undergoing cardiac surgery," Eur J Cardiothorac Surg, vol. 39, pp. 33–7, 1 2011. [PubMed: 20627611]

[8]. Dumurgier J, Elbaz A, Ducimetière P, Tavernier B, Alpérovitch A, and Tzourio C, "Slow walking speed and cardiovascular death in well functioning older adults: prospective cohort study," BMJ, vol. 339, 2009–11-10 00:00:00 2009.

[9]. Purser JL, Kuchibhatla MN, Fillenbaum GG, Harding T, Peterson ED, and Alexander KP, "Identifying frailty in hospitalized older adults with significant coronary artery disease," J Am Geriatr Soc, vol. 54, pp. 1674–81, 11 2006. [PubMed: 17087693]

[10]. Studenski S, Perera S, Patel K, Rosano C, Faulkner K, Inzitari M, et al., "Gait speed and survival in older adults," JAMA, vol. 305, pp. 50–8, 1 5 2011. [PubMed: 21205966]

[11]. Verghese J, Wang C, Lipton RB, Holtzer R, and Xue X, "Quantitative gait dysfunction and risk of cognitive decline and dementia," J Neurol Neurosurg Psychiatry, vol. 78, pp. 929–35, 9 2007. [PubMed: 17237140]

[12]. Abellan van Kan G, Rolland Y, Andrieu S, Bauer J, Beauchet O, Bonnefoy M, et al., "Gait speed at usual pace as a predictor of adverse outcomes in community-dwelling older people an

International Academy on Nutrition and Aging (IANA) Task Force," J Nutr Health Aging, vol. 13, pp. 881–9, 12 2009. [PubMed: 19924348]

[13]. Cesari M, Kritchevsky SB, Newman AB, Simonsick EM, Harris TB, Penninx BW, et al., "Added value of physical performance measures in predicting adverse health-related events: results from the Health, Aging And Body Composition Study," J Am Geriatr Soc, vol. 57, pp. 251–9, 2 2009. [PubMed: 19207142]

[14]. Cesari M, Kritchevsky SB, Penninx BW, Nicklas BJ, Simonsick EM, Newman AB, et al., "Prognostic value of usual gait speed in well-functioning older people--results from the Health, Aging and Body Composition Study," J Am Geriatr Soc, vol. 53, pp. 1675–80, 10 2005. [PubMed: 16181165]

[15]. Ostir GV, Kuo YF, Berges IM, Markides KS, and Ottenbacher KJ, "Measures of lower body function and risk of mortality over 7 years of follow-up," Am J Epidemiol, vol. 166, pp. 599–605, 9 1 2007. [PubMed: 17566063]

[16]. Rolland Y, Lauwers-Cances V, Cesari M, Vellas B, Pahor M, and Grandjean H, "Physical performance measures as predictors of mortality in a cohort of community-dwelling older French women," Eur J Epidemiol, vol. 21, pp. 113–22, 2006. [PubMed: 16518679]

[17]. Woo J, Ho SC, and Yu AL, "Walking speed and stride length predicts 36 months dependency, mortality, and institutionalization in Chinese aged 70 and older," J Am Geriatr Soc, vol. 47, pp. 1257–60, 10 1999. [PubMed: 10522962]

[18]. Fritz S and Lusardi M, "White paper: "walking speed: the sixth vital sign"," J Geriatr Phys Ther, vol. 32, pp. 46–9, 2009. [PubMed: 20039582]

[19]. Afilalo J, Eisenberg MJ, Morin JF, Bergman H, Monette J, Noiseux N, et al., "Gait speed as an incremental predictor of mortality and major morbidity in elderly patients undergoing cardiac surgery," J Am Coll Cardiol, vol. 56, pp. 1668–76, 11 9 2010. [PubMed: 21050978]

[20]. Afilalo J, Eisenberg MJ, Morin J-F, Bergman H, Monette J, Noiseux N, et al., "Gait Speed as an Incremental Predictor of Mortality and Major Morbidity in Elderly Patients Undergoing Cardiac Surgery," Journal of the American College of Cardiology, vol. 56, pp. 1668–1676, 2010. [PubMed: 21050978]

[21]. Afilalo J, "Frailty in Patients with Cardiovascular Disease: Why, When, and How to Measure," Curr Cardiovasc Risk Rep, vol. 5, pp. 467–472, 10 2011. [PubMed: 21949560]

[22]. Graham JE, Ostir GV, Fisher SR, and Ottenbacher KJ, "Assessing walking speed in clinical research: a systematic review," J Eval Clin Pract, vol. 14, pp. 552–62, 8 2008. [PubMed: 18462283]

[23]. Bohannon RW, "Population representative gait speed and its determinants," J Geriatr Phys Ther, vol. 31, pp. 49–52, 2008. [PubMed: 19856549]

[24]. Bohannon RW, "Measurement of gait speed of older adults is feasible and informative in a home-care setting," J Geriatr Phys Ther, vol. 32, pp. 22–3, 2009. [PubMed: 19856632]

[25]. Breniere Y and Do MC, "When and how does steady state gait movement induced from upright posture begin?," J Biomech, vol. 19, pp. 1035–40, 1986. [PubMed: 3818673]

[26]. Bohannon RW, "Comfortable and maximum walking speed of adults aged 20–79 years: reference values and determinants," Age Ageing, vol. 26, pp. 15–9, 1 1997.

[27]. Soangra R, Lockhart TE, and Van de Berge N, "An approach for identifying gait events using wavelet denoising technique and single wireless IMU," Proceedings of the Human Factors and Ergonomics Society Annual Meeting, vol. 55, pp. 1990–1994, 2011.

[28]. Lockhart TE, Soangra R, Zhang J, and Wu X, "Wavelet based automated postural event detection and activity classification with single imu - biomed 2013," Biomed Sci Instrum, vol. 49, pp. 224–33, 2013. [PubMed: 23686204]

[29]. Steffen TM, Hacker TA, and Mollinger L, "Age- and gender-related test performance in community-dwelling elderly people: Six-Minute Walk Test, Berg Balance Scale, Timed Up & Go Test, and gait speeds," Phys Ther, vol. 82, pp. 128–37, 2 2002. [PubMed: 11856064]

[30]. Shrout PE and Fleiss JL, "Intraclass correlations: Uses in assessing rater reliability," Psychological Bulletin, vol. 86, pp. 420–428, 1979. [PubMed: 18839484]

[31]. Fleiss JL, The design and analysis of clinical experiments: Wiley, 1986.

[32]. Wilson CM, Kostsuca SR, and Boura JA, "Utilization of a 5-Meter Walk Test in Evaluating Self-selected Gait Speed during Preoperative Screening of Patients Scheduled for Cardiac Surgery," Cardiopulm Phys Ther J, vol. 24, pp. 36–43, 9 2013. [PubMed: 23997690]

[33]. Soangra R, Lockhart TE, Lach J, and Abdel-Rahman EM, "Effects of hemodialysis therapy on sit-to-walk characteristics in end stage renal disease patients," Ann Biomed Eng, vol. 41, pp. 795–805, 4 2013. [PubMed: 23212801]

[34]. Lockhart TE, Barth AT, Zhang X, Songra R, Abdel-Rahman E, and Lach J, "Portable, Non-Invasive Fall Risk Assessment in End Stage Renal Disease Patients on Hemodialysis," ACM Trans Comput Hum Interact, pp. 84–93, 2010. [PubMed: 22124286]

[35]. Graham JE, Ostir GV, Kuo YF, Fisher SR, and Ottenbacher KJ, "Relationship between test methodology and mean velocity in timed walk tests: a review," Arch Phys Med Rehabil, vol. 89, pp. 865–72, 5 2008. [PubMed: 18452733]

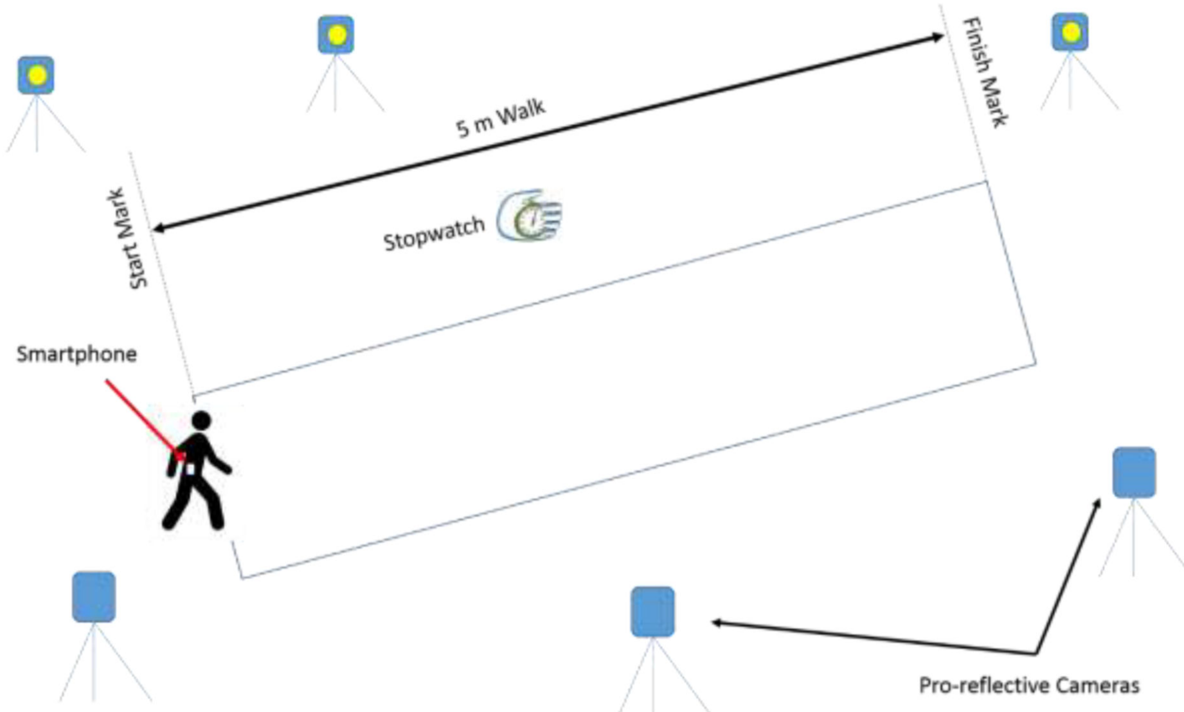

Figure 1:
Laboratory set-up for determining gait velocity in healthy participants

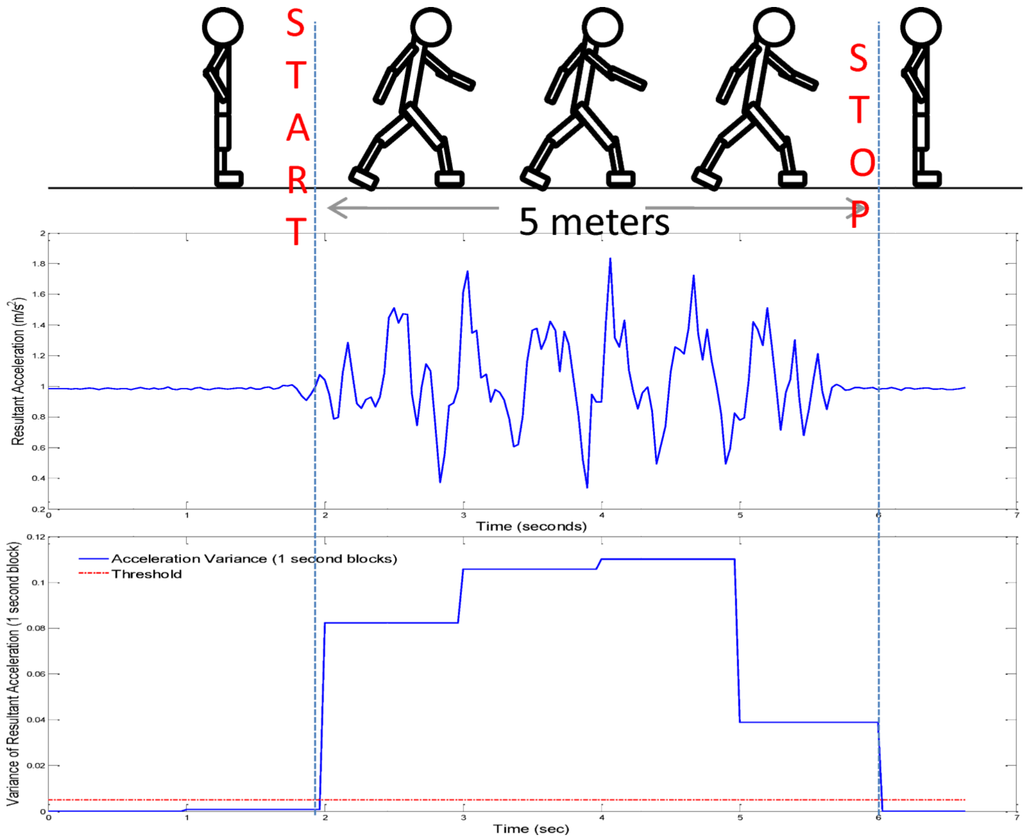

Figure 2:
The start and stop events described by the resultant acceleration and the variance. The start event is triggered when the variance exceeds the threshold (dashed red line). The stop event is triggered when the variance drops below the threshold.

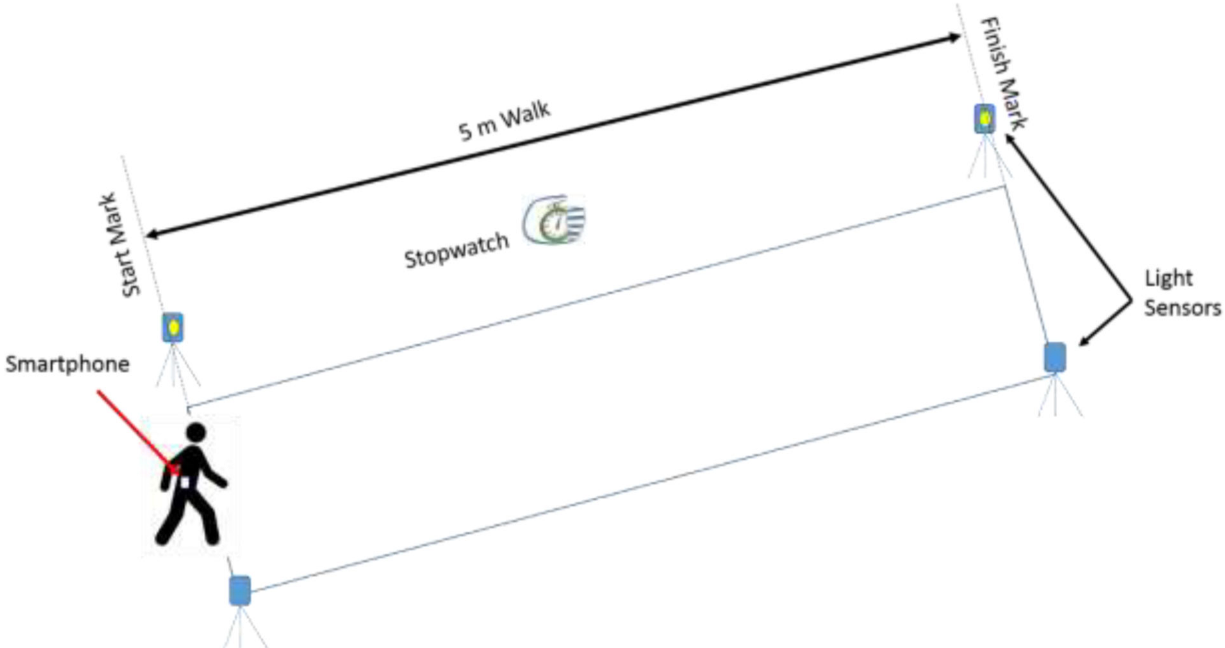

Figure 3:
Clinical set-up for determining gait velocity in cardiac patients.

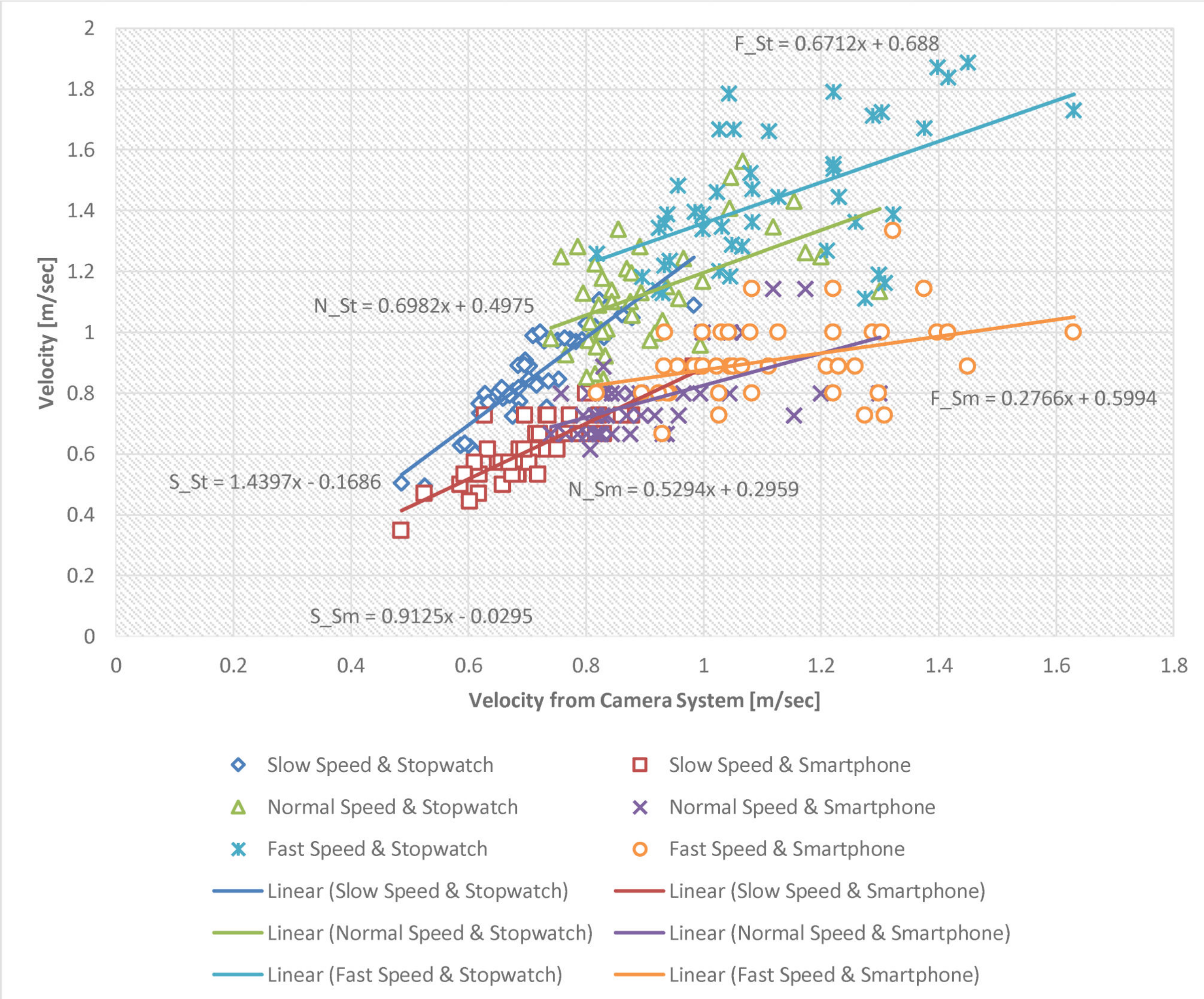

Figure 4:

Above figure shows relationship among (slow, normal and fast walking) velocities from camera system and that by stopwatch and smartphone in laboratory environment

Figure 5:

Walking speed trials measured concurrently through systems:1. Camera system 2. Stopwatch and 3. Smartphone

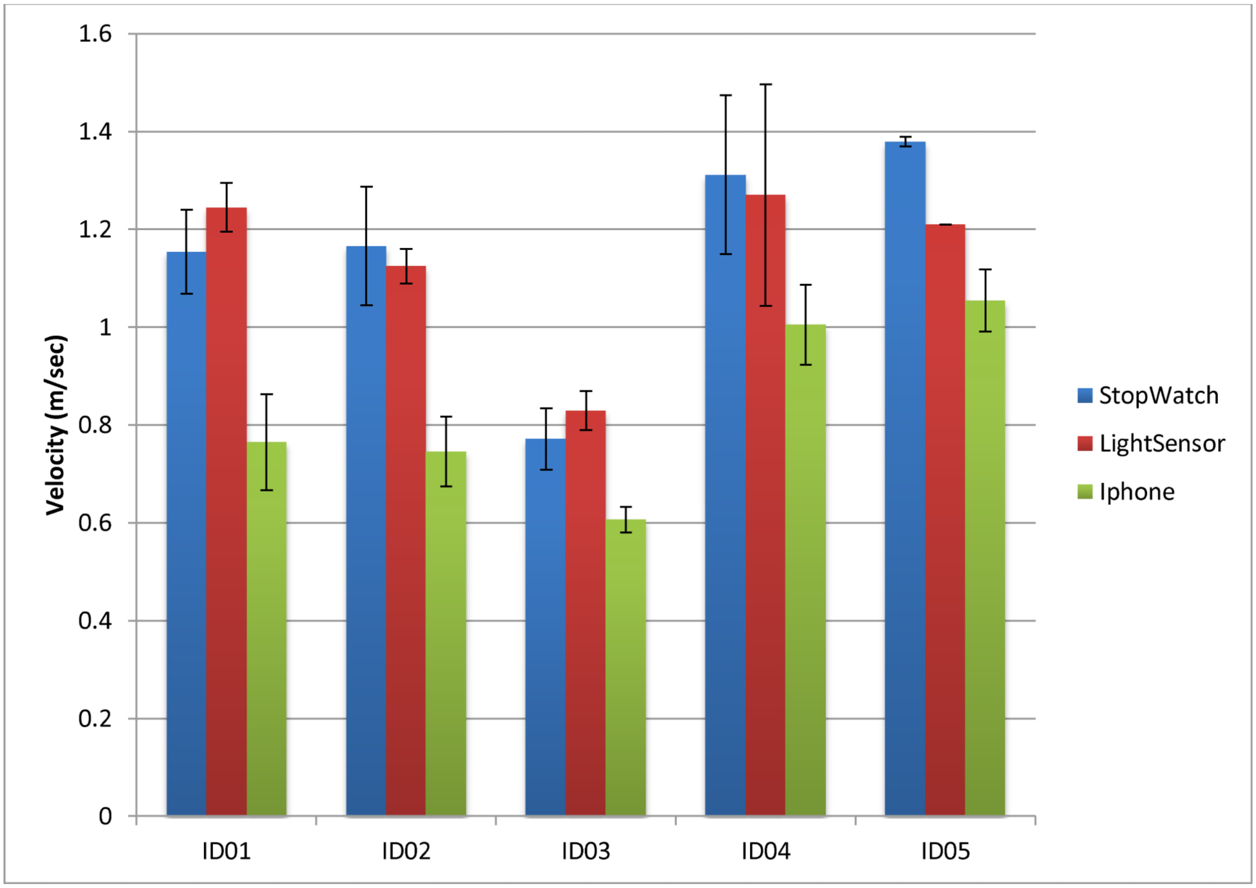

Figure 6:
Velocities from three measurement systems in clinical environment

Table 1:

Intra-class correlation for consistency and absolute agreement for three walking speed and three systems (camera, stopwatch and smartphone)

Walking speed	Intra-class correlation Consistency	Intra-class correlation Absolute Agreement
Slow	0.821	0.559
Normal	0.666	0.419
Fast	0.701	0.404