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Automated 6-Minute Walk Test Distance Measurement and Walk Characterisation using a Novel Infrared Sensor-Based Technique

(Ujian Ukuran Jarak Berjalan Kaki Automatik 6-Minit dan Pencirian Berjalan menggunakan Teknik Inframerah Berasaskan Sensor Baru)

Isniza Ismail*, Leela T. Narayanan, Rumaisa Abu Hasan & Eko Supriyanto

ABSTRACT

It is common to use motorised and non-motorised treadmills in settings with space constraints for a 6-minute walk test (6MWT). This test used manual methods which are susceptible to errors. It is believed that automated techniques could eliminate the shortcomings, but this approach was not proposed by any studies. This study presented and analysed the validity of a newly-developed automated infrared-based treadmill walking monitoring system (iTMS), which as specifically designed to measure the distance and characteristics for the walk performance of a non-motorised treadmill 6MWT (nMT6MWT). This study selected 20 subjects for: The validity testing of the iTMS walked distance at five different speeds dictated by metronome beats for 2-minute and at a self-paced speed with intermittent rests for 6-minute, and the characterisation of 6-minute walk performance for distance, speed, acceleration, walking segments, and resting events. The iTMS measured distances were consistently accurate for the varying speeds during the 2-minute walk session. For the 6-minute walk en bloc and its three segments, the difference in distance (Δd) between iTMS (d_{iTMS}) and camera recording method (d_{CRM}) showed positive biases with small LOA95% in Bland-Altman plot. The iTMS has an accurate distance measurement with ± 0.20% error of d_{CRM} for en bloc 6-minute walk can characterise the resting events of 0.5 s and more. The iTMS is considered a viable automated method for monitoring distance and characterising nMT6MWT. It also showed the potential in addressing technical errors which may be inherent in manual 6MWT data collection methods.

Keywords: Automated data collection; infrared-distance sensor; non-motorised treadmill; validity; 6-minute walk distance

ABSTRAK

Treadmil bermotor dan tidak bermotor lazim digunakan untuk mengendalikan ujian berjalan 6-minit (6MWT) dalam set berkekangan ruang. Ujian ini menggunakan kaedah manual yang terdedah kepada ralat. Teknik automatik mungkin dapat mengatasi kekurangan tersebut, akan tetapi, pendekatan ini belum pernah diusulkan. Kajian ini membentangkan dan mengkaji validasi sistem pemantauan berjalan atas treadmil berasaskan sensor inframerah automatik (iTMS), yang direka untuk mengukur jarak dan mencirikan prestasi berjalan atas treadmil tidak bermotor bagi 6MWT (nMT6MWT). Kajian ini telah memilih 20 subjek untuk: ujian validasi jarak berjalan iTMS pada lima kelajuan yang berbeza yang ditentukan oleh rentak metronom selama 2-minit dan pada kelajuan kendiri dan hentian berjeda untuk tempoh 6-minit, dan pencirian prestasi berjalan selama 6-minit bagi jarak, kelajuan, pecutan, segmen berjalan dan insiden berehat. Jarak yang diukur iTMS didapati tepat dan konsisten untuk kelajuan yang berbeza untuk sesi berjalan 2-minit. Bagi sesi berjalan 6-minit en bloc *dan tiga segmen, perbezaan jarak (Δd) antara iTMS (d_{iTMS}) dan kaedah rakaman kamera (d_{CRM}) menunjukkan bias positif dengan LOA95% yang kecil pada plot Bland-Altman. iTMS mempunyai kejituan pengukuran jarak dengan ralat ± 0.20% berbanding dengan dCRM bagi sesi 6-minit* en bloc*, dan menunjukkan keupayaan mencirikan insiden rehat bertempoh 0.5 s dan ke atas. iTMS merupakan kaedah automatik yang mampu memantau jarak dan mencirikan nMT6MWT. Ia juga menunjukkan potensi untuk menangani ralat teknikal yang mungkin wujud dalam kaedah pengumpulan data 6MWT secara manual.*

Kata kunci: Jarak berjalan 6-minit; pengumpulan data automatik; sensor jarak inframerah; treadmil tanpa motor; validasi

Introduction

Six-minute walk test (6MWT) is commonly used for cardiorespiratory exercise capacity evaluation in clinical practice (Leuchte et al. 2004; Noonan & Dean 2000; Oga et al. 2000; Vancampfort et al. 2011). The American Thoracic Society (ATS) guideline on 6MWT stated that the test is performed in straight hallways or corridors by walking on a 30 m enclosed and marked track and making quick turns around the turning cone located at both ends of the track (ATS 2002). However, there are limitations in using the hallways such as space constraints (Camargo et al. 2009; de Almeida et al. 2009; Elazzazi et al. 2012; Janaudis-Ferreira et al. 2010; Lenssen et al. 2010; Olper et al. 2011; Stevens et al. 1999) and the difficulty in monitoring the physiological parameters (Olper et al. 2011; Stevens et al. 1999) while the patients are on the walkway locomotion.

In recent years, smartphone application technology has been used for administering 6MWT (Brooks et al. 2015; Capela et al. 2015). However, the samples used in these two studies comprised of able-bodied healthy population (Capela et al. 2015) and a clinical population without any musculoskeletal limitation (Brooks et al. 2015). Although smartphone technology has its advantages, this approach might not be suitable for individuals with issues such as frailty, gait abnormality, balance problems, and physical disabilities. Hence, motorised treadmills (MT) were introduced as a viable alternative to overcome these issues (Camargo et al. 2009; de Almeida et al. 2009; Elazzazi et al. 2012; Olper et al. 2011; Stevens et al. 1999).

MTs are electronically equipped to configure and control the belt speed and action, which can be used to set the walking pace for the users. However, MT-based walking is different from overground walking as the inherent motor control of the device can influence the individual's voluntary pacing, acceleration, and deceleration (Camargo et al. 2009). The preferred choice is non-motorised treadmills (nMT) as they are not electronically controlled and the users need to rely on their efforts to move the treadmill belt (Janaudis-Ferreira et al. 2010). Although nMT walking may cause greater fatigue, they are better in simulating over-ground walking and they are considered as a safer option for some clinical populations.

The main outcome of 6MWT is the walking distance achieved in six minutes (6MWD). The treadmills used in clinical settings have built-in sensors with distance resolutions of at least 0.1 miles or 160 m which is depicted as unit increments on the treadmill display consoles to measure the walking distance (Elazzazi et al. 2012; Paradigm Health & Wellness Inc. 2014). This approach may not be able to detect standard error of measurement (SEM) in distances between the repeated walks during 6MWT evaluation, as small as 23 m (pre-rehabilitation) and 18 m (post-rehabilitation) between the two walks in MT6MWT (Olper et al. 2011) and 20 m to 25 m between three walks in nMT6MWT (Janaudis-Ferreira et al. 2010). SEM is necessary for the calculation of minimal detectable changes (MDC) which is the minimum amount of true change in the performance that is independent of changes caused by variability in measurements (de Vet et al. 2006). There are other techniques used for a more precise measurement such as attaching rolling wheels and odometers to the nMT (Janaudis-Ferreira et al. 2010) and MT (Elazzazi et al. 2012; Olper et al. 2011; Stevens et al. 1999) and calculating the complete belt revolutions in six minutes (de Almeida et al. 2009) but there was no validity for the aforementioned methods to detect MDC in 6MWD.

In addition, resting events need to be monitored and documented during 6MWTs when assessing 6MWD (ATS 2002). This task is commonly performed manually, and it may be subject to human errors. Currently, there is no documented evidence on the electronically monitored 6MWTs with the capacity to provide automated measurement of 6MWD, including the accounts on walk events and its parameters such as rest duration, walk speed, and acceleration to construct comprehensive walk profiles. The profiles were considered clinically relevant in obtaining information on 6MWD and further details on how the walks were accomplished to provide a better comparison of the patients' clinical status between the tests.

Thus, this study presented the automated monitoring system installed on an MT to capture the walking profiles which comprised of distance, speed, acceleration, resting events, and walking segments of individuals during the 6-minute duration. The infrared-based treadmill monitoring system (iTMS) used an infrared sensor module to detect the treadmill belt movements and compute the parameters. It is also equipped with automated data storage features which can remove the need for technical assistance; hence, reducing the susceptibility of human errors and simplifying the process of data collection. For system validation, the findings were compared with the distance measured using camera recordings during the walking sessions. The following are the main objectives of this study: develop the iTMS, and analyse the validity of the iTMS in collecting and storing data on the walking profiles of 6-minute walk for the use in nMT6MWTs.

MATERIALS AND METHODS

DESIGN AND DEVELOPMENT OF ITMS

The iTMS was tested on an nMT (Exerpeutic 100XL Magnetic Manual Treadmill). The treadmill has a built-in sensor with a large distance resolution of 0.1 miles = 160.93 m, and the distance values displayed on the console panel were not used in this study. An infrared (IR) line tracking sensor module that has IR emitter and detector attached to the bottom surface of the running deck facing the left side of the 2.35 m treadmill belt. It is marked with 47 small white squares with a constant distance of 0.05 m between each square (Figure 1). Thin white lines are drawn at a 0.01 m-scale along the whole length on the right side of the belt to facilitate the recordings of a camera placed at the right side of the nMT.

PRINCIPLE OF OPERATION OF ITMS

During the rotation of treadmill belt, the IR light emitted from the sensor would either be absorbed by the black surface between the white squares or reflected by the white squares so that the IR detector could detect it. The signals from the IR sensor are continuously detected at 1 kHz sampling frequency and sent to a motion detection program (MDP) so that they could be uploaded to Arduino Uno R3 microcontroller (Figure 2(A)) to compute distance, instantaneous speed, and acceleration. Continuous change of sensor signals resulting from consecutive states of absorption and reflection reflected walking activity while no change in signals (time > 0.5 s) indicated inactivity or

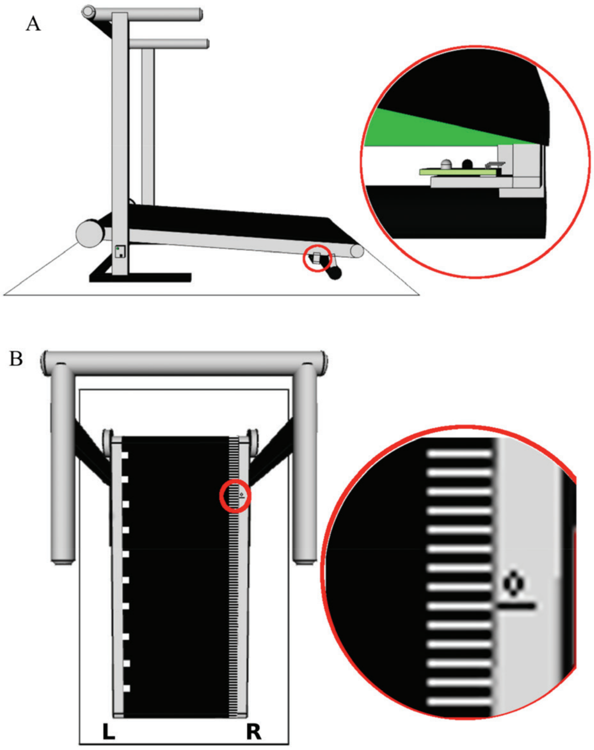


FIGURE 1. (A) Positioning of IR sensor for iTMS under the treadmill running deck and (B) drawings of 0.01 m (R) - and 0.05 m (L)- scaled thin white lines along the right and left sides of treadmill belt

a resting event (Figure 2(B)). The timer of each walking test was triggered when it detected any change in sensor signal at the beginning of the test which was programmed to continue for six minutes. The MDP captured the walking profile as well as categorising and displaying it in real-time minutes and walking segments with the timestamps (Figure 3(A)). The data were post-processed using Matlab® to visualise the walking performance of the subjects (Figure 3(B)).

PARTICIPANTS

This study has selected 20 participants (10 males, 10 females, age: 27.5 ± 2.7 years, height: 164.1 ± 5.6 cm, weight: 68.0 ± 12.5 kg) which received ethics approval from the Medical Research and Ethics Committee (Ministry of Health, Malaysia) NMRR-16-1798-32559. This study obtained the informed consents and the participants completed the PAR-Q form for their fitness level to perform the treadmill walking test.

EXPERIMENTAL DETAILS

The experiment comprised of two sessions of treadmill walking within one day. For each test, a digital camera (Sony DSC-W110) was placed near the right side of treadmill base to record the rotation of treadmill belt and the final distance after the last complete rotation. The

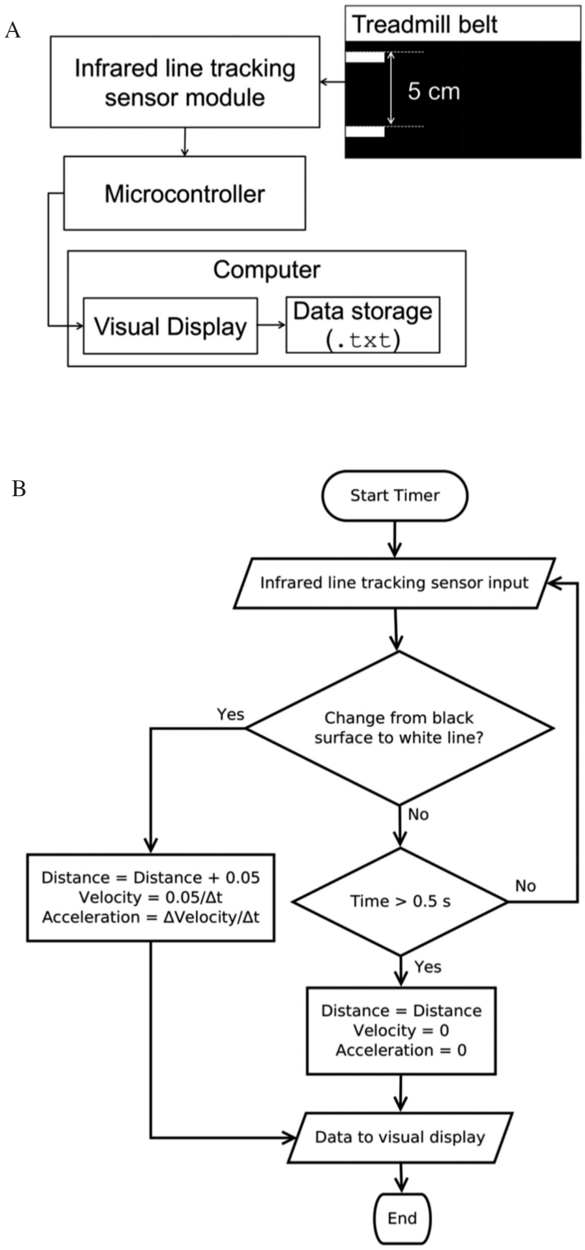


FIGURE 2. (A) Block diagram and (B) flow of the MDP for iTMS

complete rotation of treadmill belt was counted when the 0 m-white line passed the initial position (Figure 1(B)). The total distance walked by the participants was measured using the camera recording method (CRM) at the end of the test using the following calculation: d_{CRM} = number of complete rotation × 2.35 m + final recorded distance at the initial position. The measurements of d_{CRM} were taken as actual distance and compared with the distance measured by iTMS (d_{iTMS}) to verify the accuracy of the system.

Session 1 - Walking at five different speeds for 2-minute duration

The purpose of this session was to gauge the error in the walking distance between the iTMS and camera recording

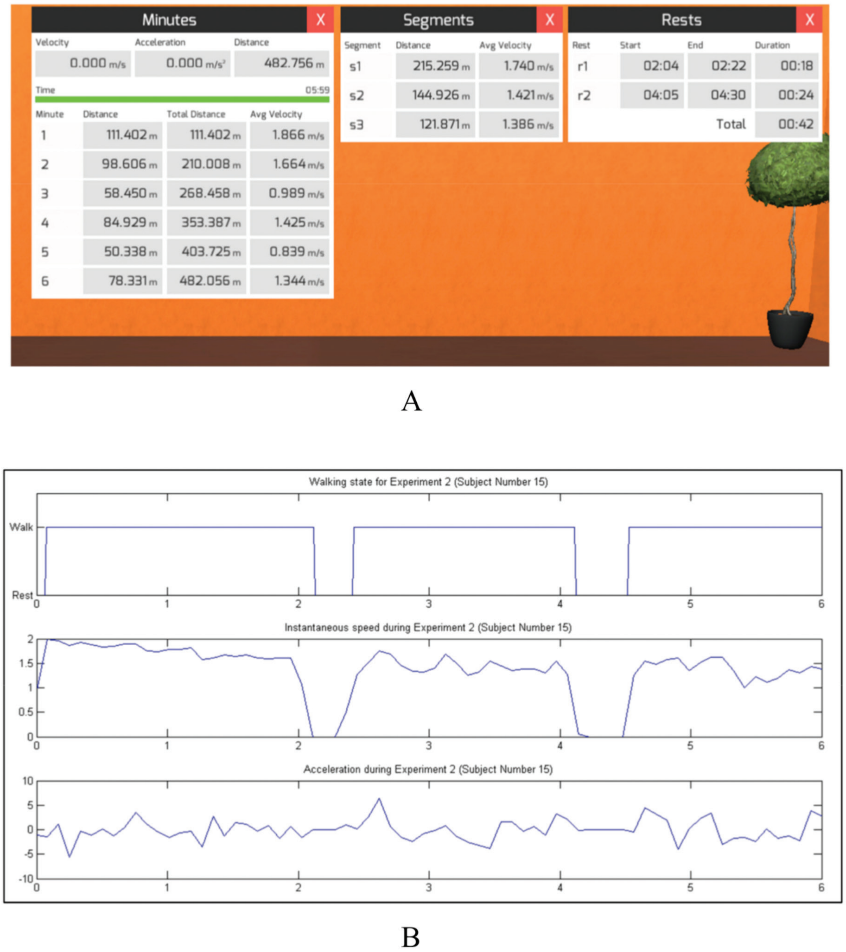


FIGURE 3. (A) Real-time visual display and (B) post-processed signal of iTMS

at various speeds. The error threshold for iTMS was set at 10% for the video recording which was the criterion before proceeding to ensure minimal error when the participants walked at varied speeds in the second session. It was also to determine the changes in error margins during the walk with different speeds. The participants performed the 2-minute duration of treadmill walk for five times at the increasing speeds dictated by different metronome beats (40, 60, 80, 100, and 120 beats per minute (bpm)). Each speed level was repeated twice (2 trials × 5 speed = 10 tests) with ten min resting interval that provided a total of 40 measurements.

Session 2 - Walking at a self-paced speed with intermittent rests for 6-minute duration

This session obtained the 6-minute walking profile to determine its validity in measuring 6MWD. It began 30 min after the first session in which the participants were given a briefing on the session procedures and they were given a chance to perform self-paced walking with rest in between. It is followed by the actual recording sessions of the self-paced walking for six min with at least two random rests.

STATISTICAL ANALYSIS

Influence of metronome beat levels This study used two way repeated measures ANOVA for the 2-minute walk duration to determine whether the differences in the distances accrued by measuring methods were the result of interaction between the measuring methods (CRM and iTMS) and metronome beat levels (40, 60, 80, 100, and 120 bpm). The sphericity could not be assumed for the ANOVA test, and Greenhouse-Geisser correction was used to adjust the degree of freedom. Then, this study performed the post-hoc analysis using Bonferroni correction and the findings were significant. The significance level of inferential analyses was set at $p < 0.05$.

Validity of iTMS The distance measured by iTMS was validated by the degree of agreement and accuracy of the standard practice of CRM using Bland-Altman plot in which the mean and standard deviation of the differences ($\Delta d = d_{CRM} - d_{iTMS}$) reflected the systematic and random errors, and they were computed to assess the presence of bias and agreement between the two methods (Bland & Altman 2003, 1986). If there was any bias, the distribution of Δd was tested for normality using Shapiro-Wilks test (Razali & Wah 2011) and further compared to the zero-value using one sample t-test (t_{df}) or Wilcoxon sign rank test (Z). The variation of Δd, which reflected the random error in distance measurement (Hanneman 2008; van Stralen et al. 2008) was quantified as 95% limits of agreement ($LOA_{95\%}$) of Δd (Bland & Altman 2003). This study calculated the absolute percentage error ($e_{\%}$) to determine the weight of measurement error to the actual distance d_{CRM}.

$$\overline{\Delta d} = \frac{1}{n}\sum \Delta d$$

$$\Delta d_{\%} = \frac{\Delta d}{\left(\frac{d_{CRM} + d_{iTMS}}{2}\right)} \times 100$$

$$95\% LOA = \overline{\Delta d_{\%}} \pm 1.96 \times sd_{\Delta d_{\%}}$$

$$e_{\%} = \frac{1}{n}\sum \left| \frac{d_{CRM} - d_{iTMS}}{d_{CRM}} \right| \times 100$$

The Δd of each segment was compared to Δd of en bloc 6-minute walk using the paired sample t-test (t_{df}) or Wilcoxon sign rank test (Z). The tests were used to determine whether the same potential errors between iTMS and CRM persisted throughout the 6-minute duration.

Characterisation of the 6-minute walk duration
Characterisation was conducted for the following parameters: distance; speed; acceleration; walking segment such as distance, speed, and frequency; rest event such as timestamp (start and end of rest event); duration; and frequency. The frequencies of resting events (r_e) and walking segments ($w_s = r_e + 1$) were observed via the video recordings (f_{CRM}) of the 6-minute walk which were compared to the frequencies detected by iTMS (f_s).

Results

INFLUENCE OF METRONOME BEAT LEVELS

The metronome beat levels ($F_{(4,156)} = 643.815, p = 0.000, \eta_p^2 = 0.943$) had a significant effect on the walking distance for the 2-minute duration, in which the post-hoc analysis using Bonferroni correction showed that the distances were significantly different between each metronome beat level (Table 1).

The two-way repeated measures ANOVA of the 2-minute walk test showed no interaction effect between the measuring methods and metronome beat levels ($F_{(4,156)} = 1.526, p = 0.215, \eta_p^2 = 0.038$).

VALIDITY OF iTMS

Each metronome level of the 2-minute walk had non-significant Δd to zero-value (40 bpm: $t_{(39)} = 0.511$, $p = 0.612$; 60 bpm: $Z = -1.123, p = 0.261$; 80 bpm: $t_{(39)} = -1.529$, $p = 0.134$; 100 bpm: $Z = -1.290, p = 0.197$; 120 bpm: $Z = -1.156$, $p = 0.248$), $e_{\%}$ less than 0.1% of the d_{CRM}, and a small $LOA_{95\%}$ of $\Delta d_{\%}$ as observed in the respective Bland-Altman plot (Figure 4(A)).

In the 6-minute walk and its three segments, Δd were significantly different from zero-value (En bloc: $t_{19} = 5.888$, $p = 0.000$; w_{s1}: $t_{19} = 6.743$, $p = 0.000$; w_{s2}: $Z = -3.92$, $p = 0.000$; w_{s3}: $Z = -3.823$, $p = 0.000$). The results showed positive biases with small $LOA_{95\%}$ when plotted in the Bland-Altman plot between the two methods (Table 1 & Figure 4(B)). Segment 3 had a similar Δd ($Z = -0.597$, $p = 0.55$) to the en bloc 6-minute walk, whereas Segment 1 ($t_{19} = 5.289$, $p = 0.000$) and 2 ($Z = -3.547$, $p = 0.000$) had a significantly smaller Δd compared to the en bloc. The $e_{\%}$ was less than 1% for both en bloc 6-minute walk and the three segments (Table 1).

CHARACTERISATION OF THE 6-MINUTE WALK DURATION

The frequencies of r_e and w_s detected by iTMS were identical to the CRM for the 19 respondents and there was one discrepancy with iTMS that detected five r_e, six w_s and CRM, three r_e, and four w_s.

Discussion

The metronome beats between 40 and 120 bpm had successfully simulated the speed levels between 0.36 and 1.06 m/s which was demonstrated in the significant differences for the 2-minute walk distances between each metronome beat level. The walking speed is positively correlated to the accumulated distance (Wootton et al. 2014) which confirmed that the iTMS could collect the walking performance data at different speed levels. Additionally, the speed did not influence the distances measured by any methods as reflected by the lack of significant interaction between the measuring methods and different metronome beat levels. Without any bias, it is suggested that the negligible systematic error in the iTMS during the 2-minute walk between d_{iTMS} and d_{CRM} in $LOA_{95\%}$ and $e_{\%}$ may be due to the random error from the differences in the resolutions between the two methods. The accuracy of iTMS in measuring the distances despite the changes in speed during the 2-minute walk showed its capacity to monitor the walk at varying speeds during nMT6MWT.

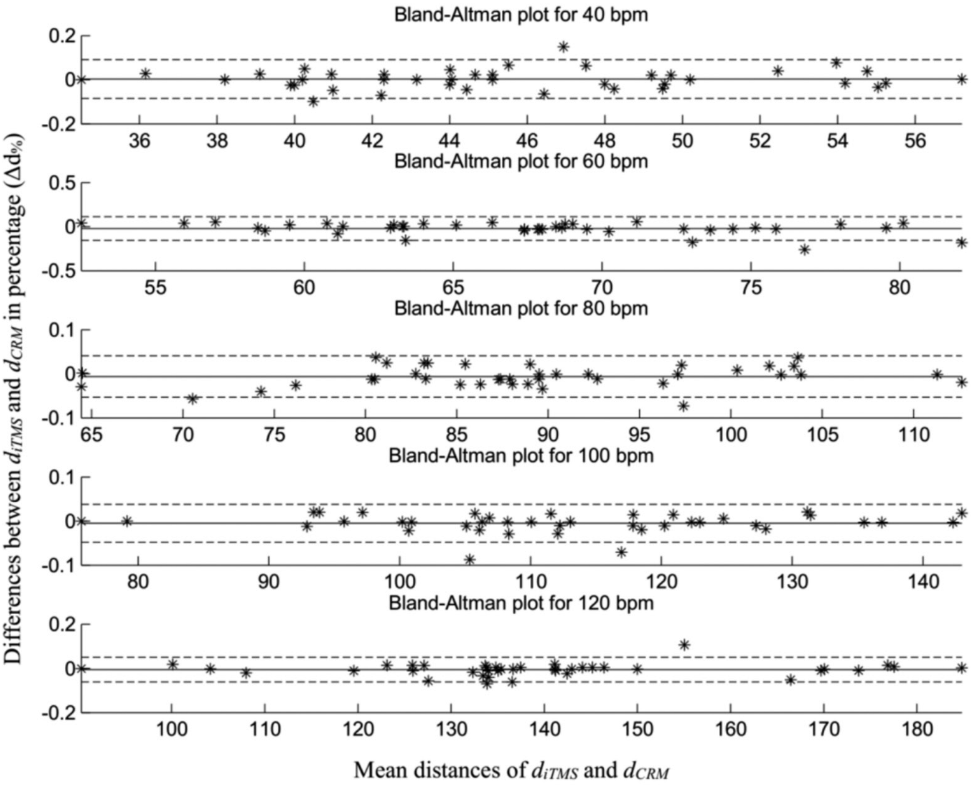
However, there were significant differences in Δd in relation to zero-value that indicated the presence of an error in the distance measurements during the 6-minute walk session. There were positive biases in the en bloc 6-minute walk and all of the three segments, which showed some limitations in the iTMS. It is believed that all the white lines drawn on the treadmill belt might not be detected during the movement, which caused smaller d_{iTMS} values. This issue caused a significant error from accruing Δd. For the similar magnitude of Δd between en bloc 6-minute walk (0.69 m) and Segment 3 (0.53 m), the error might be due to subjective discrepancies as d_{CRM} was determined

TABLE 1. Results of 2-minute and 6-minute walk performances

2 minutes	d_{iTMS}(SD) (m)	sp_{iTMS}(SD) (m/s)	d_{CRM}(SD) (m)	Δd(CI) (m)	$\Delta d_{\%}$ (LOA)	$e_{\%}$(CI)
40 bpm	45.64 (5.64)	0.36 (0.08)	45.64 (5.64)	0.00 (-0.01-0.01)	0.00 (-0.09-0.09)	0.03 (0.02-0.04)
60 bpm	67.56 (7.07)	0.50 (0.17)	67.55 (7.05)	-0.01m(-0.02-0.01)	-0.02 (-0.15–0.11)	0.05(0.03–0.07)
80 bpm	89.08 (11.16)	0.68 (0.20)	89.07 (11.16	-0.01 (-0.02-0.00)	-0.01 (-0.06–0.04)	0.02 (0)
100 bpm	112.46 (15.62)	0.90 (0.22)	112.46 (15.62	0.00m(-0.01-0.00)	-0.01 (-0.05–0.03)	0.01 (0.00–0.02)
120 bpm	139.29 (20.88)	1.08(0.30)	139.28 (20.88	0.00m (-0.01-0.01)	-0.01 (-0.07–0.05)	0.02 (0.01–0.03)
6 minutes	d_{iTMS}(SD) (m)	sp_{iTMS}(SD) (m/s)	d_{CRM}(SD) (m)	Δd(CI) (m)	$\Delta d_{\%}$(LOA)	$e_{\%}$(CI)
En bloc	349.22 (102.33)	2.25 (1.11)	349.91 (102.44)	0.69* (0.46–0.92)	0.20 (-0.11–0.51)	0.20 (0.13–0.27)
Segment 1	143.96 (77.60)	1.09 (0.36)	144.05 (77.59	0.09* (0.06–0.12)	0.18(-0.72–1.08)	0.17 (-0.03-0.37)
Segment 2	107.17 (56.76)	1.10 (0.33)	107.28 (56.76	0.09*m (0.06-0.12)	0.41(-2.24–3.06)	0.40 (-0.17–0.97)
Segment 3	81.71 (38.36)	1.06 (0.35)	82.32 (38.49	0.53*m (0.13-0.89)	0.77 (-0.75–2.29)	0.76 (0.43–1.09)

* Comparison to zero-value is significant at 0.05 level (2-tailed)
m Value given in median ([n-1.96×sqrt(n)]/2 – [2+n+1.96×sqrt(n)]/2)
diTMS: distance of iTMS; sps: speed of iTMS; dCRM: distance of CRM; Δd%: percentage differences of distances; LOA: 95% limits of agreement; e%: absolute error percentage; CI: 95% Confidence interval

A



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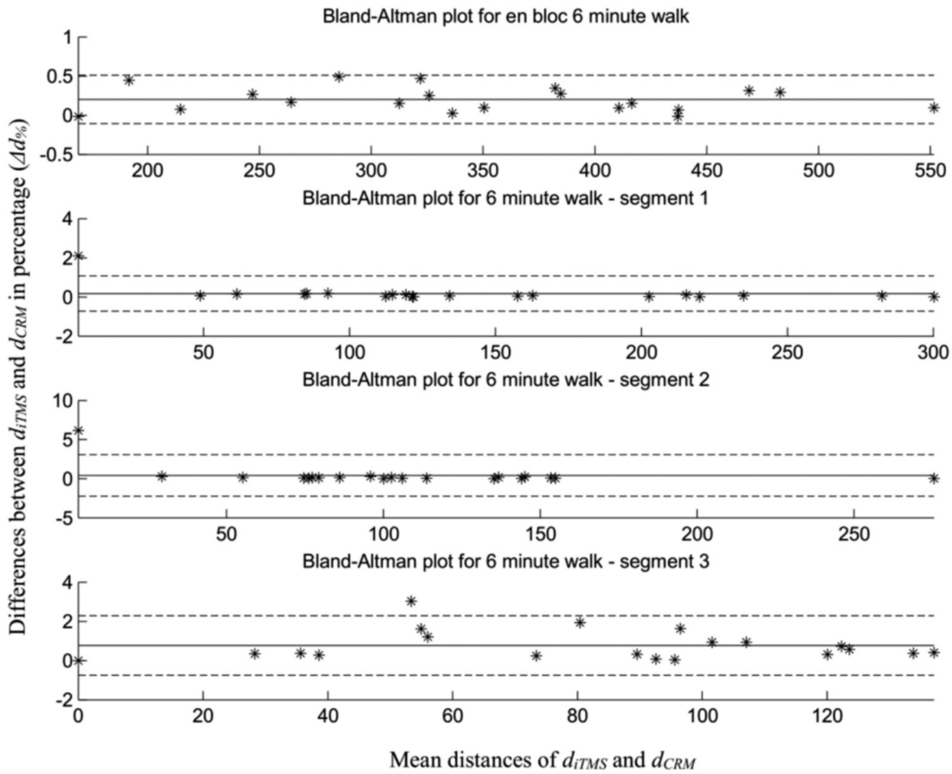

FIGURE 4. (A) 2-minute and (B) 6-minute walks using Bland-Altman plots

by eyeballing the point of completion of the walk. On the other hand, iTMS was programmed to end data acquisition precisely at t = 6.00 min. This issue was not observed in session 1 as the 2-minute point was within the time range of iTMS. However, there was a high degree of agreement between d_{iTMS} and d_{CRM} measurements which were based on treadmill belt movements as reflected by the small $LOA_{95\%}$ which was much lower than the value reported in studies on the reliability between repeated 6MWDs (Janaudis-Ferreira et al. 2010; Olper et al. 2011).

The number of resting events and walking segments detected by iTMS and CRM were identical for the duration of more than 1 s. However, the duration between the fourth and fifth r_e for one subject was less than 1 s, and it was detected by the iTMS but missed by the technical staff monitoring the CRM. This issue showed that technical errors might occur when using manual methods to determine the short duration r_e during the 6-minute walk performance. The resting events monitored by iTMS were not limited to the frequency but also the start and end timestamp as well as the duration of each event. The monitoring features are useful for patients with chronic diseases such as obstructive pulmonary disease, interstitial lung disease, bronchiectasis, and asthma who usually rest frequently during 6MWT (Jenkins & Cecins 2011).

CONCLUSION

In conclusion, this study showed that iTMS is a valid and accurate method for gauging 6MWD and r_e during nMT6MWT compared to CRM. The automated approach with data storage advantages in obtaining nMT6MWT data is a viable alternative in facilitating comprehensive information extraction for clinical assessments and interventions. Furthermore, the 6MWT walk profile created in addition to 6MWD could provide new perspectives for objective comparison to indicate the deterioration or improvement in the walking performance between the test evaluations. However, it is important to validate parameters such as speed and acceleration in the walking profile as they were not investigated in the present study. Further research is needed to determine the clinical relevance and potential of the walking profile in providing pertinent information on functional capacity.

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