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Validity of an Interactive Functional Reach Test

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Abstract

Introduction: Videogaming platforms such as the Microsoft (Redmond, WA) Kinect® are increasingly being used in rehabilitation to improve balance performance and mobility. These gaming platforms do not have built-in clinical measures that offer clinically meaningful data. We have now developed software that will enable the Kinect sensor to assess a patient's balance using an interactive functional reach test (I-FRT). The aim of the study was to test the concurrent validity of the I-FRT and to establish the feasibility of implementing the I-FRT in a clinical setting.

Subjects and Methods: The concurrent validity of the I-FRT was tested among 20 healthy adults (mean age, 25.8 ± 3.4 years; 14 women). The Functional Reach Test (FRT) was measured simultaneously by both the Kinect sensor using the I-FRT software and the Optotrak Certus® 3D motion-capture system (Northern Digital Inc., Waterloo, ON, Canada). The feasibility of implementing the I-FRT in a clinical setting was assessed by performing the I-FRT in 10 participants with mild balance impairments recruited from the outpatient physical therapy clinic (mean age, 55.8 ± 13.5 years; four women) and obtaining their feedback using a NASA Task Load Index (NASA-TLX) questionnaire.

Results: There was moderate to good agreement between FRT measures made by the two measurement systems. The greatest agreement between the two measurement system was found with the Kinect sensor placed at a distance of 2.5 m [intraclass correlation coefficient $(2,k) = 0.786$; $P < 0.001$] from the participant. Participants with mild balance impairments whose balance was assessed using the I-FRT software scored their experience favorably by assigning lower scores for the Frustration, Mental Demand, and Temporal Demand subscales on the NASA/TLX questionnaire.

Conclusions: FRT measures made using the Kinect sensor I-FRT software provides a valid clinical measure that can be used with the gaming platforms.

Introduction

Low-cost and technologically sophisticated videogaming platforms such as Nintendo (Kyoto, Japan) Wii® and Microsoft (Redmond, WA, USA) Kinect® are increasingly being used by physical therapists, clinicians, and researchers for promoting recovery in patients who have lost mobility and function.[1,2] The Kinect sensor pairs an infrared emitter with an advanced infrared video camera to create a three-dimensional map of objects and individuals located within its field of view.[3] The Kinect sensor can thus capture an individual's kinematic variables associated with his or her movements, while he or she performs movements within this mapped area. The individual's movements are also displayed on a video screen in the form of an avatar that is created by the gaming platform based on the data collected from the individual's movements in real time and provides the player with visual and performance feedback.

Using the Kinect for physical rehabilitation in a patient population offers functional activities that can be used as part of a task-oriented approach[4] in retraining balance and lost movement patterns, and it provides this intensive training in an entertaining manner that keeps the patient engaged and motivated. This increased engagement has been shown to result in patients being compliant with their rehabilitation program, resulting in more optimal outcomes and improvements in function.[5] Previous studies that have used the Kinect sensor in rehabilitation have specifically assessed this increased potential for engagement in rehabilitation activities by the patient. In a recent study that involved 12

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participants with diverse neurological disorders, structured interview questions were used to assess the user's experience following a program of Kinect-based rehabilitation.[6] The consensus reached by the participants of this study was that the Kinect gaming platform was both exciting and fun to use, and they wanted to use the device again. Similar results were also observed in a study performed in a pediatric population with degenerative ataxia.[7] The Kinect sensor, although a low-cost device, has the capability to perform a three-dimensional (3D) motion capture and analysis.[8,9] The Kinect sensor can be purchased for approximately $200, and previous studies have shown that it is feasible to perform 3D motion capture with this low-cost sensor.[10–12] A recent study demonstrated that body position measurements obtained from the Kinect are comparable to measurements obtained from more sophisticated 3D motion capture systems.[3]

One of the limitations of using gaming platforms such as the Kinect for rehabilitation involves the data that are generated from playing the game. All currently available Kinect system–based games allow players to accumulate points for successful completion of in-game activities. Such scores are useful for player engagement, can be useful for tracking a player's skill development over multiple sessions of gameplay, and provide data that have limited value to a clinician when evaluating a patient's progress. Instead of relying on in-game point-scoring systems, it would be advantageous if the gaming platform could provide built-in capability or supplementary software that can assess the patient's progress using clinical outcome measures, such as the Timed Up and Go Test, 6-Minute Walk Test, etc. These outcome measures have been validated[13,14] and are well known to clinicians. Scores generated from clinical outcome measures also provide a measure of progress that can be compared with normative values to gauge a patient's performance or can be used for comparison against a cohort of similar patient populations.

The Functional Reach Test (FRT) is a clinical outcome measure that could be assessed using the Microsoft Kinect. FRT provides a reliable, precise, and clinically accessible approximation of the excursion of the center of pressure as a patient reaches forward toward his or her margin of stability.[15] It has excellent test–retest reliability ($r = 0.89$)[16] and inter-rater reliability ($r = 0.99$).[17] A previous study also found that the FRT can be used to estimate physical frailty in the elderly population.[16] FRT scores below 6 inches have been associated with a substantially increased risk of falls among elderly males.[18] A previous study also established that the FRT is sensitive to performance changes that result from rehabilitation.[19]

Although previous studies have performed a forward reach test using a Kinect sensor,[3,20] the FRT, as originally described by Duncan et al.,[15] has not been tested for its validity to date when measured using a Kinect sensor. Moreover, currently there is no user-friendly software that physical therapists/clinicians can use to perform an FRT where the patient can interact with a virtual avatar and obtain real-time feedback on their performance. The 3D motion-capture software and hardware that are currently available have the capability of providing real-time feedback on performance; however, they are better suited for a laboratory capture of human movement and therefore are not as portable as the Kinect sensor. Thus, the primary aim of this study was to develop stand-alone software that can help physical therapists/clinicians to perform an interactive FRT (I-FRT) using a Kinect sensor and to establish this novel I-FRT's concurrent validity among healthy adults by comparing the I-FRT's measures with the measures made by a 3D motion-capture system. The secondary aim of this study was to evaluate the feasibility of implementing this technology in a clinical setting by obtaining qualitative feedback from patients who have had the opportunity to perform a balance assessment using the I-FRT.

Materials and Methods

I-FRT software development

The FRT test is performed clinically with directional cueing and physical constraints on movement. In virtual space, there are no physical constraints or references. We designed the I-FRT software to use joint position data to construct a wireframe skeleton avatar that displayed the movements of the performer in real time. Based on the performer's initial shoulder height, two horizontal lines were added to the display to create a virtual ''pipeline,'' which placed visual constraints on vertical deviations of the reaching movement. These lines also provided visual directional cueing required for accurate performance of the reaching task. Figure 1 gives a schematic of the I-FRT setup. The I-FRT software was developed using Microsoft Visual C++ so that it can be installed as a stand-alone application.

I-FRT software validation

The primary aim of this research was to establish the validity of using the Kinect to perform the I-FRT. The concurrent validity of the I-FRT measures recorded by the Kinect using I-FRT software was established by comparing it with the measures recorded by a 3D motion-capture system (Optotrak Certus® motion-capture system; Northern Digital Inc., Waterloo, ON, Canada). The Kinect and Optotrak systems were used concurrently, taking simultaneous measurements as participants performed the I-FRT. The precision and accuracy of the 3D measurements made by the Optotrak system have been shown to be good.[21]

A sample of convenience of 20 college-aged adults (mean age, 25.8 ± 3.4 years; 14 women) from the Eugene Applebaum College of Pharmacy and Health Sciences, Wayne State University, Detroit, MI, was recruited. Participants having a recent history of surgeries, physical injuries, severe cardiorespiratory problems, or light-related seizures were excluded from the study. All participants provided an informed consent. All testing procedures and protocols were approved by the Institutional Review Board of Wayne State University. All tests and measures were completed in a single session. Each participant was given up to three practice trials. The Kinect sensor was mounted on a tripod to the participant's left, at a distance of 2.0 m, 2.5 m, or 3.0 m from a reference line marking the position of the participant's right foot. The camera-to-target distances were chosen to examine the effect of distance on the validity of I-FRT software. These distances were chosen based on typical availability of space in a clinical setting for testing purposes.

The order of distances (2.0 m, 2.5 m, 3.0 m) was randomly determined before testing. Three FRT trials were performed at the first distance with the participant reaching with his or her right arm. The process was repeated at the second and third randomly chosen distances, producing nine reaching trials in total. In the event where a participant reached

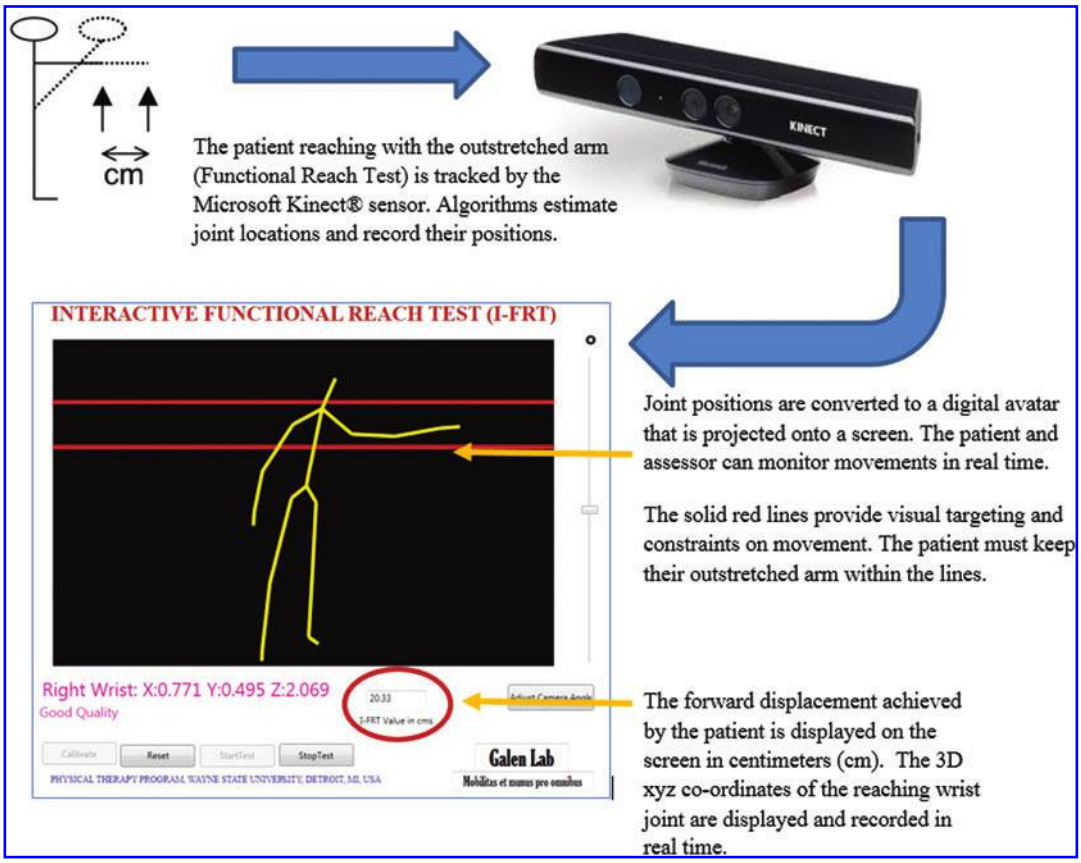

FIG. 1. Schematic showing the set-up and implementation of the Interactive Functional Reach Test. 3D, three-dimensional. Color graphics available at www.liebertonline.com/g4h

outside the boundaries of the virtual ''pipeline'' or did not perform the I-FRT correctly as specified in the guidelines, the trial was repeated. A schematic of the experimental set-up is presented in Figure 2.

FRT measurement with the Optotrak system required the placement of an infrared emitter at the ulnar styloid process of the right arm to mark the position of the wrist joint. Additional emitters were placed at the lateral epicondyle and acromion of the same arm to establish any discrepancy in measures. Static emitters were placed on a tabletop in front of the participant, 20 cm apart and in-line with the direction of reach. The emitter closest to the participant (Fig. 3) was used to establish an origin for reach calculation. It was placed a few centimeters in front of the participant's wrist. During the reaching task, the wrist emitter would cross the origin emitter twice: once at the beginning and once when the participant returned to the starting position. Thus, the Optotrak computer system uses the position of the wrist emitter and the tabletop emitter closest to the participant to calculate the length of reach and also to determine the temporal components of the reaching task. The second tabletop emitter was used to ensure that the measurements made by the Optotrak were not affected by any decrease in power to the active markers or external interference. A schematic on the measurement of the FRT using the Optotrak system is provided in Figure 3.

In order to synchronize the measurements between the Optotrak and the I-FRT Kinect system, participants were asked to hold their wrist so that the Optotrak wrist emitter was directly above the origin emitter (as established through real-time distance measurements made by the Optotrak). Once this position was attained and stabilized, the Kinect system was calibrated with this position as its origin (zero point). Thus, both systems theoretically had the same location on the reaching-direction axis as their origins. This Kinect calibration procedure was performed before every reaching trial, in order to maintain consistency.

I-FRT software feasibility study to assess clinical implementation

In order to assess the feasibility of clinical implementation of the I-FRT, a convenience sample of 10 participants with mild balance deficits (mean age, 55.8 ± 13.5 years; four women) were recruited from the outpatient physical therapy clinic at the Detroit Medical Center–Rehabilitation Institute of Michigan. Individuals who have experienced any severe cardiorespiratory problems or light-related seizures, or who were not able to perform 15 minutes of continuous activity, were excluded from the study. All individuals performed three trials of I-FRT in the outpatient clinic, and their I-FRT measures were recorded using the Kinect sensor and software. They also were provided the real-time feedback as shown in Figure 1. Following completion of the I-FRT trials, each participant provided feedback using the NASA Task Load Index (NASA-TLX) questionnaire. This validated subjective tool allowed the participants to evaluate the mental, physical, and temporal demands placed on them while performing the I-FRT and also helped them to report

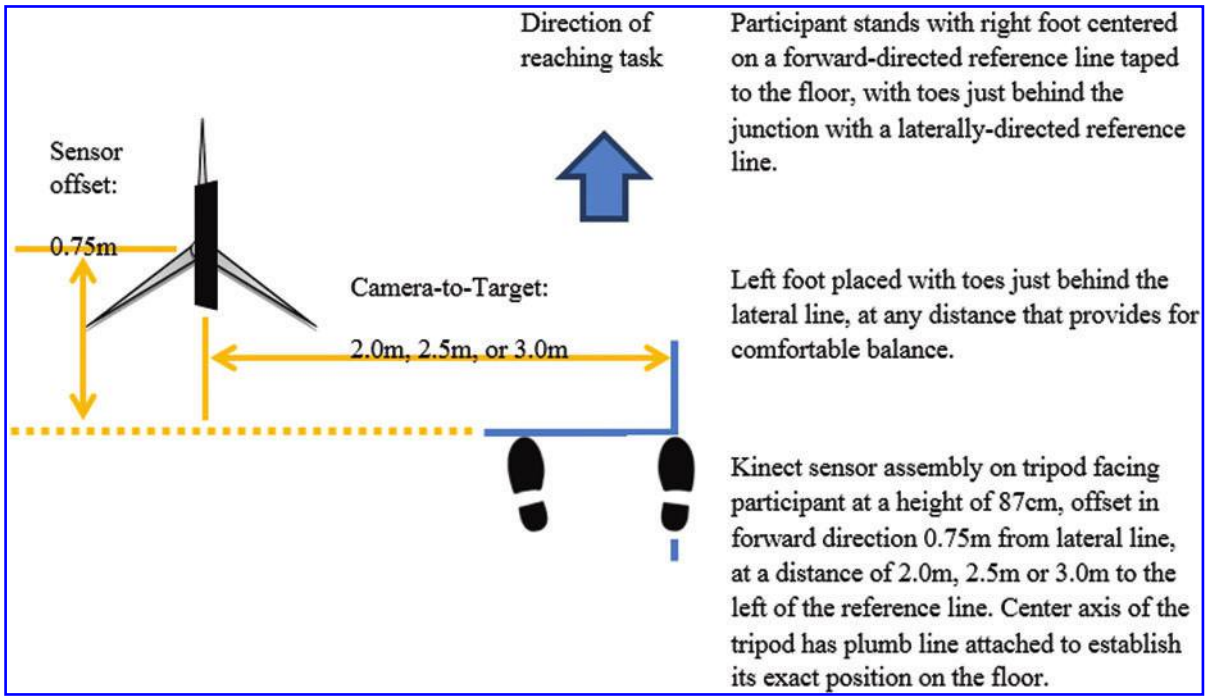

FIG. 2. The experimental set-up. Color graphics available at www.liebertonline.com/g4h

on their effort, frustration, and perceived performance.[22] All participants provided their informed consent, and all testing procedures were approved by the Institutional Review Board of Wayne State University.

Data and statistical analysis

Data collected from all reaching trials (apart from the I-FRT data collected during the feasibility study) were recorded and analyzed using SPSS version 20 software (IBM Corp., Armonk, NY). A preliminary descriptive analysis was performed to assess for trends in the data and to compute standard errors of the mean. The mean of the absolute error of measurement was computed for all nine trials. The intraclass correlation coefficient (ICC) of the type (2,*k*) with absolute agreement was used to assess the level of agreement between the measures recorded by the I-FRT and the Optotrak systems.[23] The repeatability coefficients, calculated according to Bland and

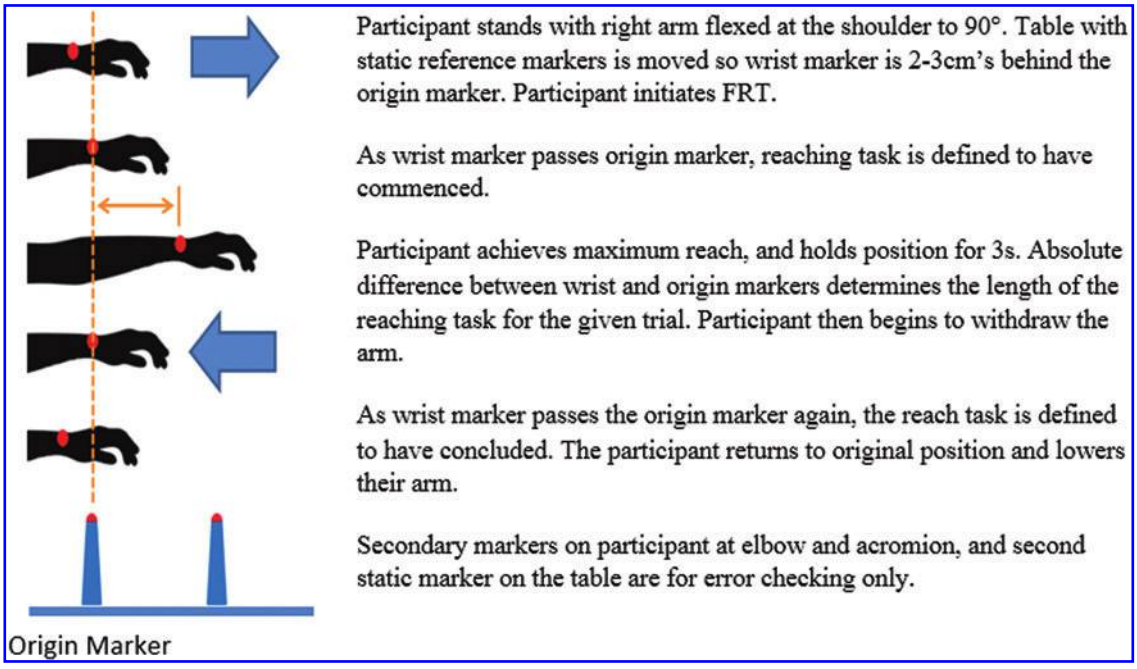

FIG. 3. Measurement of the Functional Reach Test (FRT) with the Optotrak system. Color graphics available at www.liebertonline.com/g4h

Altman[24] as 1.96 times the standard deviation (SD) of the differences between the I-FRT and Optotrak measurements, were plotted. A repeated-measures analysis of variance was performed to assess the differences between the absolute errors for the three measurement distances. Descriptive statistics such as means and SDs of the scores recorded using the NASA-TLX questionnaire were computed to assess the feasibility of clinical implementation of the I-FRT.

Results

All participants successfully completed all of the I-FRT trials. The means of the absolute measurement errors for the three distances from which I-FRT measures were recorded were as follows: at 2.0 m, 6.01 ± 4.47 cm; at 2.5 m, 4.92 ± 4.13 cm; and at 3.0 m, 4.82 ± 4.31 cm. There were no statistically significant differences ($P > 0.05$) between the absolute errors for the three measurement distances. At all distances I-FRT showed a consistent positive bias in that its FRT measures were slightly less than those observed by the Optotrak system (approximately 4–6 cm).

The ICC (2,*k*) analysis showed that the I-FRT measure of the FRT showed moderate to good agreement for the three measurement distances, when the FRT measures were compared with those of the Optotrak system. At a distance of 2.0 m the I-FRT showed a moderate agreement (ICC = 0.624, $P < 0.0001$); however, at a distance of 3.0 m the I-FRT showed good agreement (ICC = 0.713, $P < 0.0001$), and at a distance of 2.5 m the I-FRT showed good agreement with a slightly better ICC value (ICC = 0.728, $P < 0.0001$). FRT

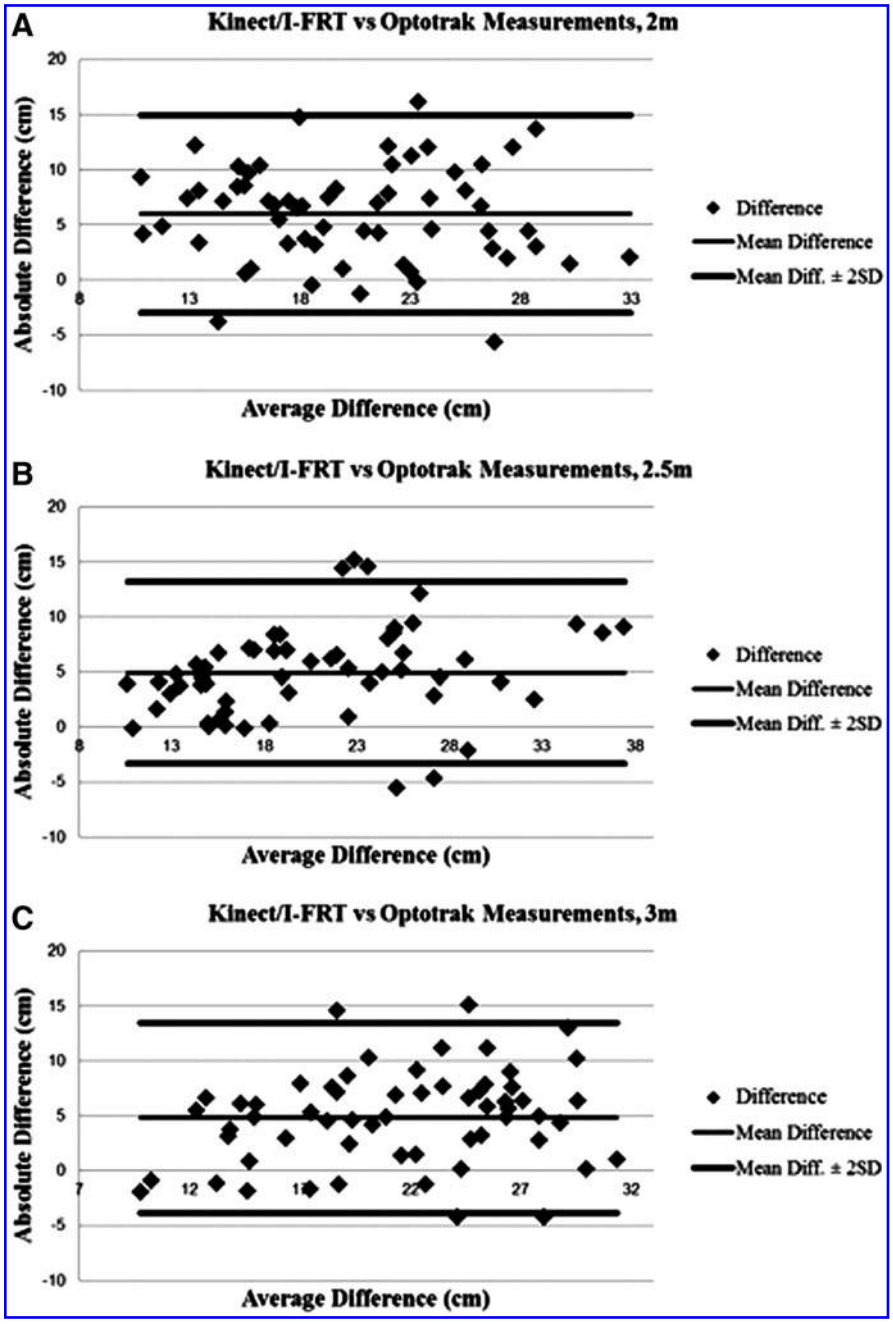

FIG. 4. Bland–Altman plots showing the distribution of absolute difference between the measures of the Interactive Functional Reach Test (I-FRT) and the Optotrak systems around the mean difference: **(A)** 2 m, **(B)** 2.5 m, and **(C)** 3 m. SD, standard deviation.

Table 1. NASA Task Load Index Results Summary

	Response	
Subscale	*Mean*	*SD*
Mental Demand	2.4	4.1
Physical Demand	4.2	4.0
Temporal Demand	2.4	4.2
Performance	3.7	3.8
Effort	4.0	4.1
Frustration	2.3	3.0

The response scores were scored on a scale of 0–20, with a low score indicating low demand effort.
SD, standard deviation.

measures recorded at both 2.5 and 3.0 m showed a good agreement with the Optotrak system.

Bland–Altman plots generated from the difference in measures of FRT between the Kinect I-FRT software and the Optotrak systems offer visual evidence that suggests that differences are of a random nature, and no proportional errors were observed (Fig. 4). The plot for 2.5 m displays data that are more closely clustered around the mean difference line in the center. Analysis of the qualitative feedback obtained using the NASA-TLX questionnaire showed that adults with mild balance deficits rated I-FRT software favorably. On a scale from very low (0) to very high (20), these participants reported low workload scores on subscales of Frustration (mean = 2.3, SD = 3.0), Mental Demand (mean = 2.4, SD = 4.1), and Temporal Demand (mean = 2.4, SD = 4.2). A complete descriptive analysis of these results is presented in Table 1.

Discussion

This study has reported for the first time the development of a stand-alone software program that can enable the Kinect sensor to perform an I-FRT. The I-FRT measure of FRT has been shown to have moderate to good agreement with measures made by the Optotrak 3D motion-capture system. The best agreement of FRT measures between the two measuring systems was observed when the Kinect sensor was placed at a distance of 2.5 m from the participant [ICC $(2,k) = 0.728$, $P < 0.0001$]. The mean measurement error observed at this distance was 4.92 cm. Measurement errors of approximately 4 cm were reported in a previous study that had investigated measurement errors produced by the Kinect sensor.[25] The measurement errors observed with forward reach in a previous study[3] were less than those reported in the present study. In this previous study the Kinect sensor was placed at a distance of 2.5 m, and the participants were asked to abduct the arm and then reach out in forward and lateral directions, which is different from our testing procedure.

The Kinect with the I-FRT software produced consistent positive bias at all Kinect camera distances (i.e., the Kinect sensor was underestimating the position of the wrist joint, ranging from 4.82 cm to 6.01 cm). With this underestimation, there is a possibility for the I-FRT software to produce false-negatives if the software is used to assess fall risk assessment. A false-negative result would amount to erring on the side of caution, implementing resources to keep a patient safe. In addition, the consistent bias produced by the Kinect is within the minimal detectable change values (which are greater than 6 cm) for the FRT for various clinical populations such as stroke[26] and Parkinson's disease.[27]

Based on the results there was no optimal camera-to-participant distance where measurement errors were minimized. Not one of the means for absolute error was statistically different from each other ($P > 0.05$). The optimal distance may not be an absolute quality (based on characteristics of the technology), but may be of relative quality (based on characteristics of patients). Other factors to consider are the patient height or arm length, characteristics that change the visual silhouette observable by the Kinect sensor. Considering these results, the Bland–Altman plots suggest that a camera distance of 2.5 m would offer the most ideal positioning for obtaining the most clinically applicable data when taking into account absolute difference in errors and their distribution around the mean (Fig. 4).

The results of the feasibility study showed that FRT measured using the I-FRT software and the Kinect sensor can be implemented in an outpatient setting. Based on the qualitative feedback from the NASA-TLX questionnaire, the patients viewed the Kinect system favorably overall. On the subscale scores, the scores were rated low to very low, with ranges from 2.3/20 to 4.2/20 (Table 1). Lower scores were given for the Frustration, Mental Demand, and Temporal Demand subscales, which suggests that patients were able to complete the Kinect task with low frustration and that they did not view it as mentally demanding. Although higher scores were given for performance, effort, and physical demand, the results are not totally unexpected given the neurological involvement of the participants.

One of the limitations of this study was that the Kinect sensor was placed at a fixed height. Therefore the height at which the Kinect sensor was placed and its effect on measurement errors are not completely understood. Since the completion of this study, Microsoft has released a more advanced Kinect sensor with better resolution. Work is currently underway to enable this new Kinect sensor to perform an I-FRT, and, in addition, tests such as the Maximum Step Length Test and Five Times Sit to Stand have also been added so that a suite of balance performance assessments can be possible using the Kinect sensor.

Conclusions

This study has shown that the Microsoft Kinect sensor using the I-FRT program is a valid instrument to measure FRT. The feasibility of implementing this system in a clinical setting has also been demonstrated. Further software upgrades and the new Kinect sensor with a better resolution are expected to decrease the measurement errors that were observed in this study.

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Author Disclosure Statement

No competing financial interests exist.

References

1. Hawn C. Games for health: The latest tool in the medical care arsenal. Health Aff (Millwood) 2009; 28:w842–w848.
2. Smith ST, Schoene D. The use of exercise-based videogames for training and rehabilitation of physical function in older adults: Current practice and guidelines for future research. Aging Health 2012; 28:243–252.
3. Clark RA, Pua YH, Fortin K, et al. Validity of the Microsoft Kinect for assessment of postural control. Gait Posture 2012; 36:372–377.
4. Vearrier LA, Langan J, Shumway-Cook A, Woollacott M. An intensive massed practice approach to retraining balance post-stroke. Gait Posture 2005; 22:154–163.
5. Brokaw EB, Eckel E, Brewer BR. Usability evaluation of a kinematics focused Kinect therapy program for individuals with stroke. Technol Health Care 2015; 23:143–151.
6. Lange B, Chang CY, Suma E, et al. Development and evaluation of low cost game-based balance rehabilitation tool using the Microsoft Kinect sensor. Conf Proc IEEE Eng Med Biol Soc 2011; 2011:1831–1834.
7. Ilg W, Schatton C, Schicks J, et al. Video game-based coordinative training improves ataxia in children with degenerative ataxia. Neurology 2012; 79:2056–2060.
8. Pfister A, West AM, Bronner S, Noah JA. Comparative abilities of Microsoft Kinect and Vicon 3D motion capture for gait analysis. J Med Eng Technol 2014; 38:274–280.
9. Svendsen MB, Preisler L, Hillingsoe JG, et al. Using motion capture to assess colonoscopy experience level. World J Gastrointest Endosc 2014; 6:193–199.
10. Stone EE, Skubic M. Passive in-home measurement of stride-to-stride gait variability comparing vision and Kinect sensing. Conf Proc IEEE Eng Med Biol Soc 2011; 2011:6491–6494.
11. Schmitz A, Ye M, Shapiro R, Yang R, Noehren B. Accuracy and repeatability of joint angles measured using a single camera markerless motion capture system. J Biomech 2014; 47:587–591.
12. Shum HP, Ho ES, Jiang Y, Takagi S. Real-time posture reconstruction for Microsoft Kinect. IEEE Trans Cybernet 2013; 43:1357–1369.
13. Hafsteinsdottir TB, Rensink M, Schuurmans M. Clinimetric properties of the Timed Up and Go Test for patients with stroke: A systematic review. Top Stroke Rehabil 2014; 21:197–210.
14. Hamilton DM, Haennel RG. Validity and reliability of the 6-minute walk test in a cardiac rehabilitation population. J Cardiopulm Rehabil 2000; 20:156–164.
15. Duncan PW, Weiner DK, Chandler J, Studenski S. Functional reach: A new clinical measure of balance. J Gerontol 1990; 45:M192–M197.
16. Weiner DK, Duncan PW, Chandler J, Studenski SA. Functional reach: A marker of physical frailty. J Am Geriatr Soc 1992; 40:203–207.
17. Bennie S BK, Dizon A, Fritz H, Goodman B, Peterson S. Measurements of balance: Comparison of the Timed ''Up and Go'' Test and Functional Reach Test with the Berg Balance Scale. J Phys Ther Sci 2003; 15:93–97.
18. Duncan PW, Studenski S, Chandler J, Prescott B. Functional reach: Predictive validity in a sample of elderly male veterans. J Gerontol 1992; 47:M93–M98.
19. Weiner DK, Bongiorni DR, Studenski SA, et al. Does functional reach improve with rehabilitation? Arch Phys Med Rehabil 1993; 74:796–800.
20. Galna B, Barry G, Jackson D, et al. Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson's disease. Gait Posture 2014; 39:1062–1068.
21. Mazumder MMG, Kim S, Park SJ. Precision and repeatability analysis of Optotrak Certus as a tool for gait analysis utilizing a 3D robot. J Eng Technol Res 2011; 3:37–43.
22. Stefanidis D, Haluck R, Pham T, et al. Construct and face validity and task workload for laparoscopic camera navigation: Virtual reality versus videotrainer systems at the SAGES Learning Center. Surg Endosc 2007; 21:1158–1164.
23. Shrout PE, Fleiss JL. Intraclass correlations: Uses in assessing rater reliability. Psychol Bull 1979; 86:420–428.
24. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986; 1:307–310.
25. Khoshelham K, Elberink SO. Accuracy and resolution of Kinect depth data for indoor mapping applications. Sensors 2012; 12:1437–1454.
26. Outermans JC, van Peppen RP, Wittink H, et al. Effects of a high-intensity task-oriented training on gait performance early after stroke: A pilot study. Clin Rehabil 2010; 24:979–987.
27. Schenkman M, Cutson TM, Kuchibhatla M, Chandler J, Pieper C. Reliability of impairment and physical performance measures for persons with Parkinson's disease. Phys Ther 1997; 77:19–27.

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