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The Effects of Everyday Concurrent Tasks on Overground Minimum Toe Clearance and Gait Parameters

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Abstract

Deaths and injuries resulting from falls are a significant problem for older adults. Over half of falls during walking result from a trip, and these are likely to begin when the foot contacts the ground at the point of minimum toe clearance (MTC) during the swing phase where the foot most closely approaches the ground. MTC is commonly investigated using a limited number of points and on a treadmill, which cannot account for flooring irregularities, speed changes, and direction changes of overground gait. This paper presents a new method of calculating 3D overground MTC that accounts for flooring variations and utilizes hundreds of points on each shoe. These methods are applied to ten unimpaired adults during habitual gait 1) without a concurrent task, 2) while carrying a 9 kg laundry basket, 3) while carrying a tray with a full glass of water on it, and 4) while answering standardized conversational questions. Results indicated that steps were slower and shorter during concurrent tasks while MTC changes were dependent on task type (higher for basket, lower for questions, and unchanged for water). Task-related MTC changes were independent of spatiotemporal gait changes. Thus, MTC during overground gait, particularly while concurrent tasks are being performed, may be an independent fall risk factor that merits further investigation in subjects at-risk of falls. The relationships between MTC, gait parameters, and older age or fall risk should be explored further in at-risk subjects and circumstances to elucidate potential tripping mechanisms.

Keywords

Gait; Minimum Toe Clearance; Tripping; Concurrent Task; Attention

1. Introduction

Falls are the leading cause of injury-related death for persons over 65, comprising nearly half (45.4%) of all deaths and more than doubling the next most frequent cause (18.4% for

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Conflict of Interest Statement

None of the authors have any financial or personal relationships with other people or organizations that could inappropriately influence or bias this work.

motor vehicle traffic) [1]. Nonfatal injuries due to falls are almost twice (1.85x) as frequent as injuries from all other causes combined in this age group [2]. Fifty-three percent of falls in healthy older adults are estimated to be due to tripping while walking [3] and the minimum toe clearance (MTC) is the local minimum distance between the shoe and ground during the swing phase of gait where these trips are likely to occur [4]. The MTC occurs at a critical instant where not only is the toe most closely approaching the ground, but the speed of the foot and toe is also at or near its maximum and the body center of mass is located anterior to the stance foot and outside of the base of support in the direction of progression [4]. If a trip occurs at or near the point of MTC, stability cannot be regained without a rapid and safe placement of the swing foot [4]. Thus, a lower or more variable MTC in a specific subject population or during a specific concurrent task performed during gait would presumably indicate an increased risk of falling due to a trip.

MTC has generally been evaluated on a treadmill [5–8], which enables the rapid collection of a large number of consistent steps, but can not account for ground height variations, obstacles, and speed or direction changes of overground gait in real-world conditions. Moreover, studies that have recorded MTC overground did not attempt to account for the ground height variations of the laboratory [4]. Considering that MTC can be less than 10mm [5], even minute variations in laboratory flooring could have significant effects on the true MTC value. Furthermore, treadmill MTC data has been shown to be non-normal [5,6], but it is unclear if overground MTC will exhibit the same effects. Accurately characterizing the distribution of MTC data is particularly important, as MTC only has to drop below zero once to instigate a trip.

Concurrent tasks performed during gait can alter gait parameters that indicate increased fall risk [9], but some of these changes cannot be captured on a treadmill. We are not aware of a study examining MTC during concurrent tasks, nor of one that evaluates MTC overground while accounting for variations in floor height. This study addresses these gaps in the literature by introducing a novel method to calculate 3D MTC and other gait parameters in unimpaired adults walking normally and walking while performing three functional concurrent tasks.

2. Methods

2.1. Subjects and Instrumentation

A convenience sample of five unimpaired men and five unimpaired women were recruited, ranging in age from 22–58 years (44±13 years). After completing the informed consent process, each subject was given instrumented shoes in their own size (model 811, New Balance Athletic Shoe, Inc., Boston, MA, USA). As this was a pilot study of a new method of minimum toe clearance (MTC) calculation and the first known assessment of MTC during concurrent tasks, no statistical power analysis was completed.

Both the shoes and floor were digitized prior to the subject testing. For the shoes, four 9.5mm retroreflective markers were mounted on threaded studs embedded in the outsole of both the heel and toe of each shoe (Figure 1). Each shoe was then mounted on a jig to immobilize it while a MicroScribe-3DX stylus digitizer (Immersion Corp., San Jose, CA, USA) was used to capture at least 20 points on each marker, 264 points on the toe area of the sole, and 189 points on the heel area of the sole.

For the floor, a custom two-marker rolling wand was used to trace a grid pattern on the floor immediately prior to subject testing using the same capture volume calibration (Figure 2). This resulted in a custom floor fit for each subject that accounted for any variations in placement of the static calibration frame on the smooth floor of the capture volume. This grid was bounded by two closely-spaced passes just outside the calibrated volume and two just inside the border to minimize over-fitting of the resulting surface fit of these data. A 12-camera Vicon MX40 system using Workstation v5.2.9 was used to collect all data at 120Hz (Vicon, Centennial, CO, USA).

2.3. Data Collection

Each subject performed ten gait passes at a “comfortable, normal” walking speed across a calibrated floor area (3.7m long × 0.6m wide) for each of the following randomly-presented conditions of habitual gait: 1) without a concurrent task (control condition), 2) while carrying a heavy (9 kg) laundry basket (basket condition), 3) while carrying a tray with a full glass of water on it (water condition), and 4) while answering standardized conversational questions (questions condition). For the basket and water conditions both hands were used to hold the object in front of the body, thus obstructing the view of the feet and the ground immediately in front of them. For the questions condition, the experimenter matched the pace of the subject as he or she approached and began asking each question just as the subject entered the calibrated floor area. The instructions given to the subjects for this condition were to listen to each question and attempt to answer it in a conversational manner.

2.4. Data Processing

After preprocessing in Workstation, all remaining data processing was completed using custom MATLAB code (The MathWorks, Natick, MA, USA). A sphere-fitting algorithm was first used to determine the center of each marker from the digitizer data. These digitizer data were then combined with the motion capture data to locate all points on the shoe sole for every frame of motion capture data. Motion capture data were then low-pass filtered at 10Hz using a 4th order Butterworth filter with forward and backward passes. This cut-off frequency was empirically selected to attenuate noise without distorting the higher-frequency marker motion at ground contact.

The floor surface was fit to the traced grid of digitized points on the floor using a high-order polynomial calculated via Polyfitn [10]. The floor of our capture volume, while appearing to be flat to the naked eye, proved to be quite tortuous across its entire length (Figure 2). Extensive testing of our floor indicated that fits between 8th and 12th order were suitable and an 11th order fit was chosen for the data presented here. No filtering was applied to the motion capture data of markers on the floor digitizing wand because the polynomial surface itself, a least-square fit of the grid comprised of all digitized points, better compensated for the random noise in the marker data.

The shoe was defined to contact the ground using a custom algorithm incorporating the minimum distance from the shoe to the floor, the minimum speed of any point on the shoe, and the change in the forward and backward differences of this minimum speed. Simple ground contact algorithms, such as when the shoe dropped below the floor surface (due to sole deformation) and the speed of the slowest point on it was <0.2 m/s worked most of the time, but they misidentified or missed many valid ground contact events and created more erroneous events and were thus not used here. Step length, width, and time were calculated from the mean positions of the heel markers on each shoe at ground contact.

2.5. Statistical Analysis

Step length, step width, step time, minimum toe clearance (MTC), and toe speed at MTC for all valid steps were combined into single mean values for each condition for each subject. As other studies have reported MTC to be non-normal [5–6], normality was evaluated using the Shapiro-Wilks test. Measures of central tendency and variability were reported for both intra- and intersubject distributions. To clarify, each intrasubject distribution consisted of a data point for each of the 19–26 gait cycles completed by each subject during the 10 trials for each task condition, while the intersubject distributions consisted of a single data point for each subject for each task condition. The dependent variables were then tested for the effect of condition and stepping foot using both mixed models and the Kruskal-Wallis one-way analysis of variance by ranks using SAS (SAS Institute Inc., Carey, NC, USA) where $p<0.05$ was considered significant. As no interaction effects or stepping foot effects reached significance, they were omitted from the analyses presented here.

3. Results

3.1. Normality of Minimum Toe Clearance Data

The only minimum toe clearance (MTC) intersubject distributions with high levels of skewness (>1) were the intrasubject means and medians of the control (i.e. no concurrent task) gait condition (Table 1). However, the intrasubject MTC skewness was high for two, five, three, and zero of the ten subjects for the control, basket, water, and questions conditions, respectively (Table 1).

Of the eight intersubject MTC data distributions tested (four conditions of both mean and median MTC), only the mean and median of MTC for the control gait condition were non-normal by the Shapro-Wilks test ($p<0.05$, Table 1). When the normality of intrasubject MTC was assessed, three, seven, three, and two of the ten subject distributions were non-normal for the control, basket, water, and questions conditions, respectively (Table 1).

3.2. Gait Parameters

Overall, steps during concurrent tasks were slower and shorter ($p\leq0.01$, Figure 3) than steps during gait without a concurrent task. Post-hoc Bonferroni multiple comparisons indicated that the questions condition significantly differed from control gait for toe speed and step length ($p<0.03$) and toe speed for the water condition was also significantly slower than control ($p=0.006$). Step width was unaffected by concurrent task ($p=0.9$).

3.3. Minimum Toe Clearance (MTC)

Results of mixed models testing indicated that the effect of concurrent task on MTC was significant for mean (p=0.009) and for median (p=0.01) and the direction of this effect varied with the specific concurrent task (Figure 4). Although the multiple comparisons did not reach significance, MTC was lower for the questions condition, higher for the basket condition, and relatively unchanged for the water condition. When the variability of MTC was tested, the task effect was significant for standard deviation (p=0.0006) but not for intraquartile range (p=0.06). The direction of these effects followed a similar pattern as the means and medians and no multiple comparisons reached significance. All significant mixed models effects were similarly significant for the Kruskal-Wallis test (p=0.008, 0.01, 0.003, and 0.12 for effects listed above). Follow up linear correlation testing indicated that toe speed at MTC, step length, and step time were all intercorrelated (p<0.01), while mean and median MTC were uncorrelated with these three variables.

4. Discussion

Despite concerns about data normality in prior studies [5–6], normality and skewness of the data only minimally affected the minimum toe clearance (MTC) results presented here. Although the intrasubject MTC data were often non-normal and skewed, the intersubject distributions were less frequently and less severely so (Table 1). While the median (10.0mm with 4.1mm IQR) may better represent some of the intrasubject data, it remains quite similar to the mean (10.3mm with SD of 3.2mm) and does not alter the significance of the observed task effects. Regardless of the normality or non-normality of the data, all effects were quite similar regardless of whether or not normality was a requirement of the statistical test used.

The data presented in Table 1 might lead one to hypothesize that performing a concurrent task with gait reduces the skewness of the MTC distributions. However, the intrasubject skewness-where only fewer skewed distributions were present for the control condition than were present for either the basket or water conditions-contradicts this. While there may be some effect of concurrent task on normality and skewness of MTC distribution, this can not be definitively established by the data presented here.

The MTC data reported here from 19–26 cycles of control gait per unimpaired subject were similar to but slightly lower than data recorded previously [4–6]. This discrepancy is most likely due to methodological differences. For example, Winter calculated MTC of 12.9±4.5mm from the vertical displacement of shoe-mounted markers for young subjects traversing a level walkway at least ten times [4]. Begg and colleagues calculated MTC of 15.6±6.2mm from a single virtual marker for young subjects walking for 20 minutes on a treadmill [5]. The median and IQR for this study was 15.5mm and 3.1mm, respectively. Mills and colleagues also calculated MTC for 1,000 sequential strides on a treadmill of 10 unimpaired young subjects from a single virtual marker and reported intersubject means of intrasubject median and IQR values of 14.9mm and 4.3mm, respectively [6]. Our MTC results are most likely lower than previous data because the methods used here do not assume that MTC occurs at a specific virtual marker, but rather selects the smallest MTC from hundreds of virtual markers.

Begg and colleagues did not find the variability of MTC in older adults to differ significantly from that of younger adults [5] while Mills and colleagues found it to be higher in older adults, but this effect only just passed their level of significance (p=0.049) [6]. In contrast to age, clear task effects on MTC are evident in these data and any variability effects follow those of the means and medians. While age may indeed affect MTC, these data show that concurrent tasks are likely to affect it more strongly and possible interactions between age and concurrent tasks on MTC should be investigated.

The method of MTC calculation presented here is similar to those initially presented by Startzell & Cavanagh [11] and used by Hamel and colleagues [12], but has been expanded to include the digitization of the ground and separating the foot into toe and heel segments. The large number of digitized points on the shoe soles captured here allows the point of minimum clearance between foot and ground to be selected from a large number of possible points rather than using a single [5,6,8] or only three [13] assumed points of minimum clearance. This level of accuracy may not ultimately prove to be necessary for all or even any experimental circumstances, but this should be verified experimentally rather than assumed to be the case. Digitizing the floor surface enables the imperfections present in all floors to be corrected for-in our case the variations in height of our floor (~9mm) were in some cases greater than the MTC values calculated (mean MTC=8.1mm for questions) and thus critical to accurate measurement. Note that the section of vinyl-tile covered concrete slab floor used in this study was quite tortuous and required a high order surface for an accurate fit, but the optimal fit order and type should be established for each lab. For example, force plates are quite flat and are best fit with 2^{nd} order surfaces while sheets of plywood tend to warp smoothly and are best fit by 3^{rd} order surfaces. In the case of flat force plates embedded in non-flat walkways, piecewise surface fits are likely to be ideal. While more labor- and computationally-intensive than previous methods, the methods presented here enable MTC to be captured during gait initiation, termination, changes in speed, and turns as well as while negotiating real-world obstacles, non-flat surfaces, and slopes.

The speed parameter tested here was that of the average position of the four toe markers. This was selected from several possible measures of gait or foot speed because it was a measure of the toe segment rather that of the gait pattern in general, and because it was more consistent value than the speed of a single marker or a point on the shoe sole. All of these various measures of speed, however, exhibited similar effects.

The concurrent tasks performed were not as controlled or precise in the specific aspects of executive and motor function required as concurrent tasks typically performed during gait in laboratory settings, but this was knowingly sacrificed for ecological validity. The questions, water, and basket conditions do not cleanly evaluate executive function, vigilance, or motor control, but are real-world tasks where these aspects may dominate but are not required in isolation. As such, conclusions regarding the effects of specific aspects of concurrent tasks cannot be drawn directly from these data; instead they provide direction for subsequent studies.

The finding that steps were slower and shorter while a concurrent task was being performed was not surprising. Of greater note was that MTC increased or decreased depending on the nature of the specific concurrent task performed and was not linearly correlated with toe speed. This has critical implications to the accurate calculation of MTC, as treadmills, the predominant experimental paradigm for calculating MTC, do not allow natural gait adaptations to concurrent tasks. While we did not detect a direct linear correlation between any gait parameter and MTC, there may be some relationship between task type, compensatory gait adaptations, and MTC that would be misrepresented by constant speed treadmill gait. Recent research has shown MTC on a treadmill to decrease at 4.3mm per each additional m/s of gait speed [8], while earlier data of overground gait at different speeds reported MTC to be 8.9mm at a toe speed of 3.6m/s (slow cadence), 12.9mm at 4.5m/s (natural cadence), and 12.3mm at 5.3m/s (fast cadence) [14]. Despite some methodological differences, these contradictory findings indicate that speed-related changes in overground MTC do not appear to be equivalent to speed-related changes in treadmill-obtained MTC. The results presented here further indicate that any relationship between MTC and speed may be masked or complicated by the effects of other factors.

In conclusion, several factors warrant further investigations of MTC changes with concurrent tasks in populations at-risk of falls and in circumstances where falls are more likely to occur. Firstly, there is a more direct potential relationship between MTC and tripping (i.e., if the toe hits the ground at MTC a trip is initiated) than between other gait parameters and other mechanisms of falling. Secondly, while most spatiotemporal gait parameters have been shown to change with age [15–16], MTC (with no concurrent task) has been shown to be unaffected by age [5–6] and is here shown not to be correlated with several of these gait parameters. Thus, overground MTC, particularly during concurrent tasks, may be an independent fall risk factor that merits further investigation in subjects at-risk of falls. The relationships between MTC, gait parameters, and older age or fall risk should be explored further in at-risk subjects and circumstances to elucidate potential tripping mechanisms.

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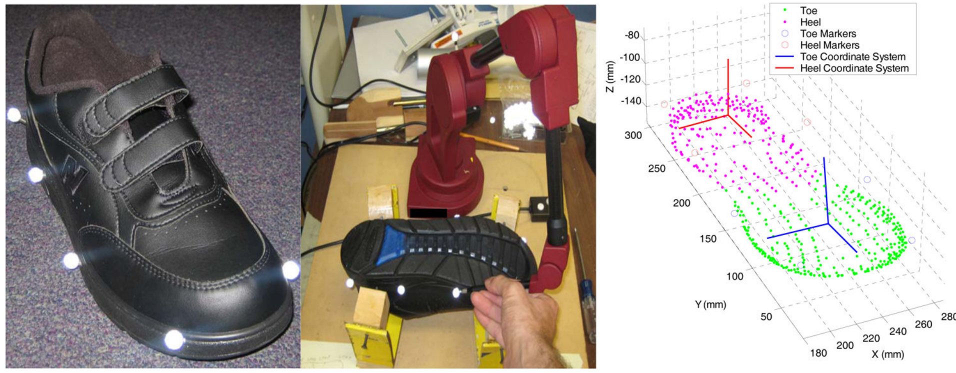

Figure 1.
Experimental shoe (left) being digitized (center) and sample data (right)

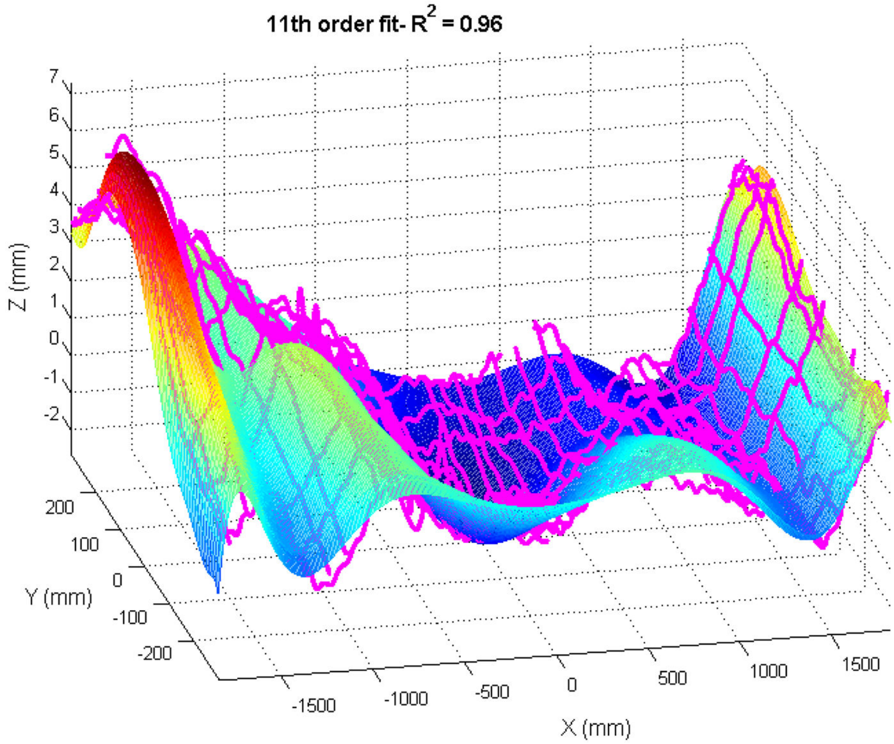

Figure 2.

Sample surface fit of the digitized floor area. Note the large differences in scale of the axes.

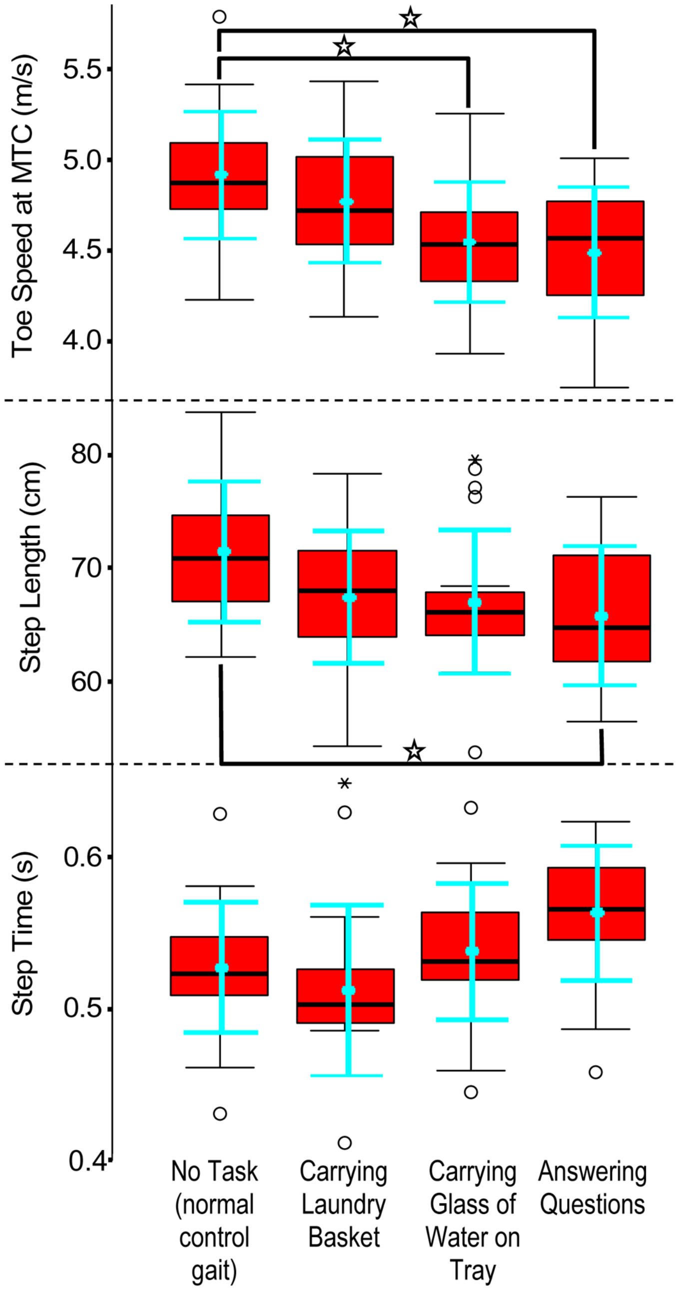

Figure 3.
Overlapping box and error bar (±1SD) plots of intrasubject gait parameter data by concurrent task for gait parameters with significant (p<0.011) concurrent task effects. Outliers (1.5–3*IQR) indicated by circles and extremes (>3*IQR) indicated by astyrixes. Significant multiple comparison effects indicated by stars.

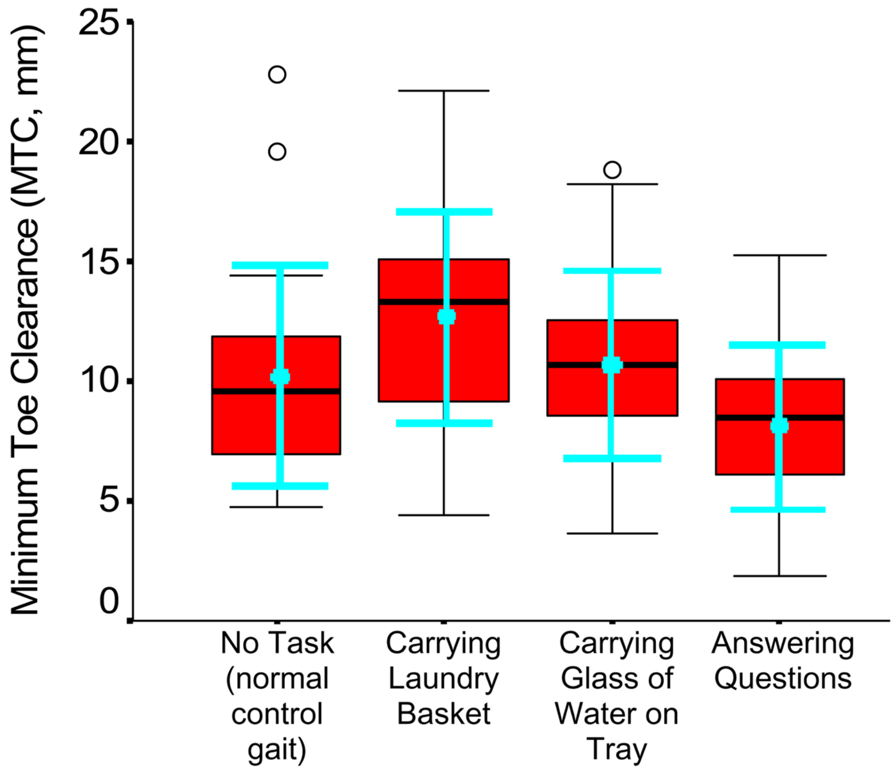

Figure 4.

Overlapping box and error bar (±1SD) plots of intrasubject means of minimum toe clearance (MTC) by concurrent task. Omnibus effect of concurrent task was significant ($p<0.01$), but no multiple comparisons reached significance. Outliers (1.5–3*IQR) indicated by circles.

Table 1

Shapiro-Wilks (SW) test results and skewness for minimum toe clearance (MTC) data between and within subjects (N=10).

Concurrent Task	Intersubject tests of…				Number of subjects with distributions that are…	
	Intrasubject means		Intrasubject medians			
	SW p-value	skewness	SW p-value	skewness	non-normal (SW p<0.05)	skewed (skewness>1)
Control	0.020	1.36	0.046	1.23	3	2
Basket	0.992	0.03	0.909	0.20	7	5
Water	0.479	0.21	0.113	0.30	3	3
Questions	0.804	0.08	0.663	−0.05	2	0