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Obstacle clearance performance in individuals with high body mass index

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ABSTRACT

The objective of this study was to quantify performance in an obstacle clearance task among individuals with excess body weight or body mass index (BMI). Task performance was operationalized as the maximum obstacle height cleared, four duration measures of successful task completion and compensatory movements used in the process of task completion. Eighteen participants with a BMI exceeding 30 kg/m^2 completed a laboratory experiment that required stepping over seven lightweight obstacles. Obstacle heights were sequentially increased from 36 cm in 5 cm increments until participants were unsuccessful or unable to clear the obstacle up to 66 cm. Successful task completions decreased from 100% at an obstacle height of 36 cm to 66.1% at 66 cm. Higher obstacle heights were associated with significantly fewer task completions, longer leading and trailing leg stance and overall task duration, and more frequent use of compensatory movements for successful obstacle clearance. Cox PH regression was used to test the association between probability of obstacle clearance and normalized obstacle height adjusting for BMI, standing balance, and type of compensatory movement used, namely, hover and pivot motions involving the leg, and hands for bracing. The probability of successful task completion significantly decreased with increases in BMI (hazard ratio, HR = 1.14, 95% CI: 1.05–1.25), and increased with use of a leg pivot motion (HR = 0.30, 95% CI: 0.09–0.96) during task completion, after adjusting for standing balance and other types of compensatory movements. Overall, the results demonstrated that obstacle clearance performance is affected by an individual's BMI and the use of compensatory behaviors for regaining stability. The ability to recruit internal and external stabilization techniques could potentially serve as a clinical indicator of reduced fall risk and be the focus of fall prevention interventions. Implications for evaluating stability, fall risk, and identifying modifiable factors for fall prevention in the obese population are discussed.

1. Introduction

Obesity, defined as having a body mass index (BMI) exceeding 30 kg/m^2 is known to increase the risk of cardiovascular and metabolic diseases including hypertension, stroke, Type II diabetes, and premature mortality (Jensen et al., 2014). Estimates from the National Health and Nutrition Examination Survey (NHANES) indicate that the prevalence of obesity among US adults aged 20 and over has nearly doubled from 22.9% in 1988–1994 to 42.4% in 2017–2018 (Chen et al., 2020). Obesity prevalence among US adults has increased by 8.7% in the past decade alone (Fryar et al., 2020). Obesity impairs functional mobility with individuals diagnosed as obese performing lower on most measures of mobility including gait speed, 6-min walk test, standing balance control, and stability during walking compared to those with BMI less than 30 kg/m^2 (Hergenroeder et al., 2011). Individuals who are obese have an increased risk of falls during activities of daily living (ADL; odds ratio, OR = 1.12, 95% CI: 1.01–1.24) and a greater risk of disability when performing ADL after a fall (OR = 1.17, 95% CI: 1.02–1.34) compared to individuals with a BMI less than 30 kg/m^2 (Himes and Reynolds, 2012).

Potential reasons for this increased fall risk and lowered balance performance include decreased postural control (Benetti et al., 2016) and increased instability due to an anterior shift in the center of body mass (Corbeil et al., 2001). Impaired balance in particular is an

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Abbreviations: BMI, Body Mass Index; ADL, Activities of Daily Living.

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important risk factor for falls, and thus also critical to fall prevention. During quiet standing, individuals who are obese and overweight swayed with higher velocity than individuals of normal weight (Hue et al., 2007; Dutil et al., 2013), while reducing body weight was shown to improve balance control among obese and overweight individuals (Teasdale et al., 2007). The negative outcomes associated with obesity are a major concern due to the rising prevalence of obesity. Although the direct link between the increased prevalence of obesity and fall-related medical costs among people with obesity is not available, obesity may independently increase the risk for a fall-related injury, and possibly, costs of post-injury treatment and care (Madigan et al., 2014) and subsequent disabilities as a result. Unintentional injuries from falls cause disabilities and fractures (Forrest and Cali, 2009), resulting in approximately 67.3 billion dollars in lifetime medical costs (Seifert, 2007). In 2015, overall medical expenditure related to fatal falls was estimated to be $754 million (Florence et al., 2018).

The risk of falls during ADLs is higher during movements that require maintaining postural balance while standing on one leg. Activities such as walking (Meng et al., 2017) and ascending or descending staircases (Jacobs et al., 2016) have a short transition involving single-leg stance. The duration of single-leg stance is more pronounced and prolonged during obstacle clearance tasks, such as stepping over a threshold and entering or exiting a bathtub. Notably, falls in bathrooms are particularly frequent among various ADLs due to the increased risk of tripping or falling when getting in and out of the tub or shower. Falls were the primary cause of injury (81.1%) among all nonfatal bathroom injuries among persons ages 15 and older in 2008 (Centers for Disease Control and Prevention, 2011). Injuries that occurred in or around the tub or shower (65.8 per 100,000) were the most frequent type of injury among all nonfatal bathroom injuries, with nearly 12.0% of such injuries occurring either when entering or exiting the bathtub (Centers for Disease Control and Prevention, 2011). Over 23.2% of bathroom-related injuries associated with the bathtub or shower result in hospitalization due to a fracture or traumatic brain injury (Sauter et al., 2015).

Stepping over obstacles is a demanding task for the locomotive system (Sparrow et al., 1996). The most prominent contributing factors to the high prevalence of nonfatal bathroom falls include need for an extended single-leg stance duration during bathtub ingress and egress, and other environmental factors such as slippery contact surfaces and surface textures (Siegmund et al., 2010; Levine et al., 2021; Cham and Redfern, 2002). Prior studies found decreased step velocity and double limb support time among obese adults as obstacle heights increased up to 20 cm (Desrochers et al., 2021). Children (4–13 years old) who were overweight or obese took longer to reach maximum knee height and to achieve foot contact; these events delimit the duration of the single-leg stance in a study with obstacle heights of 4–16 cm (Gill and Hung, 2012). Unfortunately, most prior studies investigating performance of a obstacle clearance involve obstacles with heights of 36–40 cm (14–16″), which is less than 20–25% of the participants' stature (Azevedo, 2014; Houser et al., 2008), and mostly with relatively young participants [e.g., 36 ± 8 years in Azevedo (2014)] with normal to overweight BMI (BMI <30 kg^2). In general, studies investigating obstacle clearance performance among people with obesity used much lower obstacle heights for safety reasons [e.g., maximum at 20 cm in Desrochers et al. (2021)], in which the study results have limited utility in understanding accessibility challenges with high obstacles among such populations. Considering that most commercial bathtub heights (namely, 35–51 cm; 14–20") exceed the tested maximum obstacle heights across these studies, our understanding about the movement performance of individuals with high BMI when negotiating obstacles of higher height is still limited. Also, the evidence from prior studies fail to address how individuals with a high BMI might alter or adapt their movements to meet increasing task demands or obstacle height in the present context. Therefore, this preliminary study was undertaken to explore potential measures of movement adaption during obstacle clearance, particularly at obstacle heights exceeding knee height.

The objectives of this study were twofold: (1) to quantify effects of excessive body mass (BMI >30 kg/m^2) and standing balance on performance in an obstacle clearance task; and (2) to quantify effects of obstacle height and individual characteristics including BMI and standing balance on the probability of successful obstacle clearance as a function of obstacle height. The study hypothesized that as obstacle heights increased, a higher BMI and decreased standing balance (increased postural sway, lower self-reported balance confidence) would negatively influence task performance and reduce the probability of successful task completion, both outcomes considered as proxy measures of a higher fall risk in naturalistic settings.

2. Materials and methods

2.1. Study participants

Eighteen participants (9 male, 9 female) were recruited for this study. Inclusion criteria for study participation consisted of having a BMI ≥ 30 kg/m^2, and having reported a confidence score $\geq 70\%$ (on a 0%–100% scale) on questions from the Activities-Specific Balance Confidence (ABC) Scale questionnaire related to walking independently and without ambulation aids around the house and during ascent-descent on stairs (Powell and Myers, 1995). The study was approved by the university's institutional review board. All participants provided written informed consent prior to participation.

2.2. Experiment procedures

2.2.1. Static anthropometry and balance

The experiment was conducted in an indoor laboratory setting and on a hard tile floor. Initially, participant stature (mm) and body mass (kg) were measured using a conventional anthropometer and weighing scale, respectively. The entire ABC Scale questionnaire was administered to obtain a measure of the participants' confidence in everyday ambulation tasks (Powell and Myers, 1995). The ABC Scale is a validated instrument for discriminating between levels of physical functioning (Myers et al., 1998) and is predictive of fall risk among older adults (Lajoie and Gallagher, 2004). The questionnaire has 16 items related to daily activities (e.g., walking around the house, climbing stairs, getting into or out of a car) requiring respondents to rate their level of confidence in performing each the activity without losing balance or becoming unsteady on a continuous scale from 0% (no confidence) to 100% (complete self-confidence). A final ABC score is computed as the average of all 16 item scores.

In the interest of instrumentation portability, standing balance was assessed with a body-worn inertial sensor using a previously validated procedure by Moe-Nilssen and Helbostad (2002). This involved attaching a commercial wearable accelerometer (Biostamp RC, mc10 Inc., Lexington, MA; 80 Hz sampling frequency) on the back torso above the sixth thoracic vertebra (T6) using double-sided hypoallergenic tape. One of the sensor axes was aligned with the spine and directed vertically downwards. The procedure for measuring static balance required the participant to stand upright and motionless while barefoot on levelled floor with their eyes open for 30s. Participants were instructed to have their arms across their chest and their gaze directed towards a visual target located on a wall 2 m in front at eye level. Accelerometer data was recorded for the 30-s duration at 80 Hz, and subsequently low-pass filtered with a 6-Hz second-order zero-lag Butterworth filter, and then transformed to eliminate the tilt caused by the initial torso posture and sensor orientation (Moe-Nilssen and Helbostad, 2002). Static balance was quantified by characterizing postural sway and computed as the root mean squared value of the trunk anteroposterior and mediolateral resultant acceleration (RMSacc) in the true transverse plane over the 30-s period (Moe-Nilssen and Helbostad, 2002).

2.2.2. Obstacle clearance task

The experiment required participants to step over a simulated lightweight obstacle as quickly and safely as possible without contacting the obstacle causing it to either move or topple. One obstacle was presented per trial in sequentially increasing height from 36 cm to 66 cm in 5 cm increments for a maximum of seven measurement trials. The base obstacle of lowest height (left panel in Fig. 1) was constructed from lightweight cardboard material with dimensions of 1.0 m width × 0.1 m depth × 0.36 m height. Additional cardboard blocks each 5 cm (∼2 in) in height with similar width and depth were stacked above the base obstacle to achieve a maximum height of up to 66 cm (right panel in Fig. 1). The minimum height and height increments were set based on the standard commercial bathtub height in the US market (freestanding bathtubs: 35–51 cm; 14–20", alcove and drop-in bathtubs: 40–51 cm, 16–20″) (Badeloft, 2021). The maximum obstacle height used in the study (66 cm) is beyond the standard commercial bathtub height but was included to purposefully fail participants within the given height range for the purpose of testing their limit. One end of the obstacle butted against a solid wall.

The experiment procedure used a method of limits starting from the base obstacle height to determine the maximum height that the participant could step over successfully without visible contact that either displaced and/or toppled any of the cardboard blocks as determined by the lead researcher present. Any such contact deemed the trial unsuccessful and no further trials were conducted. Participants were initially provided with a maximum of two practice trials with the base obstacle for the opportunity to identify and self-select a preferred side (i.e., having the vertical wall to either to their left or right) and a leading leg (right vs. left foot leading). They were instructed to maintain their preferred side and leading leg for all subsequent measured trials. Use of the wall for bracing was permitted during any phase of the obstacle clearance task if needed. Participants could select and/or alter their pace and direction of approach, namely, facing the obstacle forwards (anterior) or by using a lateral side-stepping motion, depending on their perceived safety and ease of successfully completing the task. A horizontal clearance space of 2 m on either side of the obstacle was provided to minimize confounding from adjacent walls and/or building elements. This clearance space required participants to take 2 or more steps both, before and after clearing the obstacle.

During the task trials, participants could adopt compensatory movement strategies for maintaining and/or regaining stability. A prior preliminary study on obstacle clearance using a video-based hierarchical task analysis had identified four types of compensatory movements that involved the legs, namely, a shuffle, pivot and hover motion involving either the leading and/or trailing leg – all reflecting internal stabilization techniques, and specific movements with one or both hands for bracing against the wall indicating external stabilization (Lim et al., 2018). Fig. 2 presents a listing and descriptions of these compensatory movement strategies.

Fig. 1. Images showing a participant stepping over the light-weight obstacle used in the study at the minimum base height of 36 cm (left) versus the maximum height of 66 cm (right).

Task trials in the present experiment were video-recorded using two cameras, one located inline with and the other perpendicular to the obstacle to capture sagittal (Fig. 1) and frontal views of the task, respectively. A video-based task analysis was conducted later to annotate the video recording for: (i) the start and end times of key gait events during the obstacle clearance trial (viz., leading leg liftoff, leading leg touchdown, trailing leg liftoff, and trailing leg touchdown) as depicted in Fig. 3, and (ii) the occurrence of compensatory movements involving the leg(s) and hand(s) based on the descriptions presented in Fig. 2. A liftoff event in Fig. 3 was defined as the first instant either foot is entirely off the ground prior to stepping over the obstacle. A touchdown event was defined as the first instant any part of the foot touches the ground on the opposite side of the obstacle after crossing. This sequence of stepping movements was observed consistently across all participants as there was no hopping or jumping over the obstacle in the study. A trained research assistant performed annotations for all videos in this study, and the first author visually cross-checked all annotations. More detailed task analysis steps can be found in Lim et al. (2018). The video-based task analysis and annotation were performed using the ELAN v5.1 software application (Nijmegen: Max Planck Institute for Psycholinguistics, The Language Archive, 2020).

2.3. Study variables

2.3.1. Individual characteristics and obstacle height

Independent variables in this study consisted of obstacle height as the within-subject variable (7 levels) and three between-subject variables, namely, BMI (kg/m^2), ABC score (0%–100%), and the inertial sensor-based measure of standing balance, RMSacc (g).

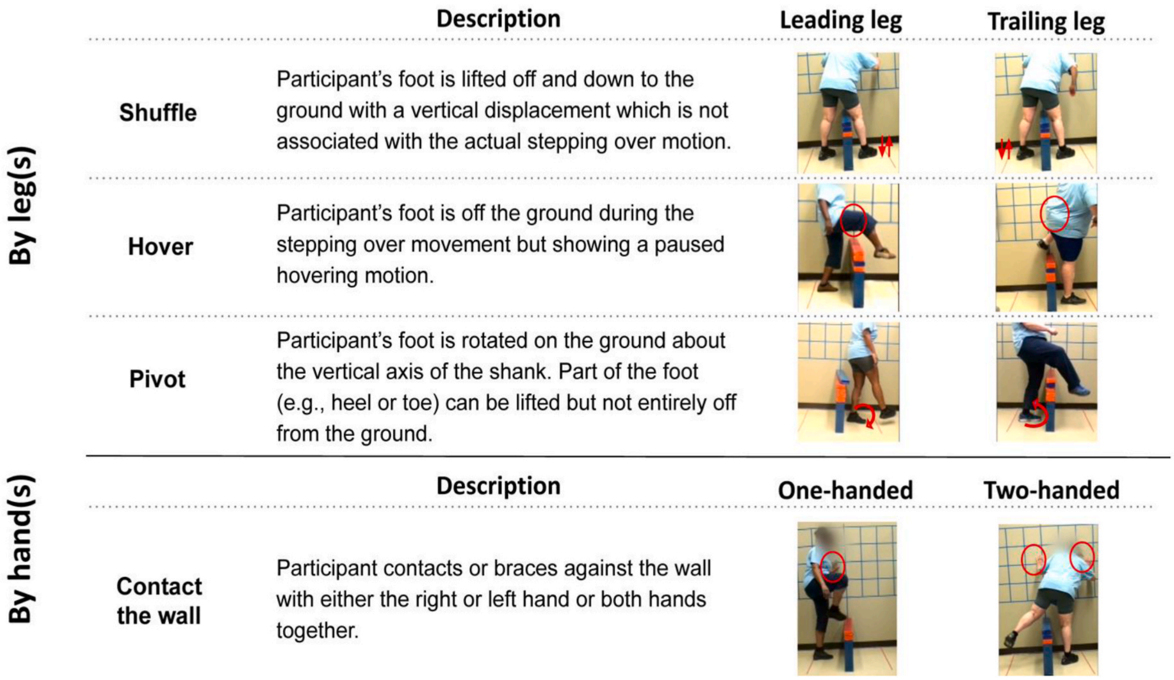
2.3.2. Performance measures

Task performance measures extracted for analysis consisted of the maximum obstacle height successfully cleared; the time duration for three main gait phases for all successful trials (viz., single-leg stance with the trailing leg, double-split stance, single-leg stance with the leading leg; refer Fig. 3) by referencing the start and end times annotated for four gait events from the video analysis; total task completion time computed as the sum of the three gait phase duration measures (i.e., from leading leg liftoff to trailing leg touchdown); and the type of compensatory movement used from among those listed in Fig. 2 for each successful trial. Participants could have used more than one type of compensatory movement during a trial. Each type of compensatory movements was coded separately as a binary value (present vs. absent) even if used multiple times. For example, participants could use their hands to brace against the wall while pivoting the stance leg. They could also use multiple strategies sequentially, such as shuffling and then pivoting in one trial.

2.4. Statistical data analysis

Statistical analyses were performed using *R v.3.6.1* (R Core Team, 2019). The mean, standard deviation (SD) and ranges were calculated for the person variables, namely, age, stature, body mass, BMI, ABC score, and RMSacc.

Study objective 1 examining task performance was addressed by way of three sub-analyses performed on data from successful trials, namely, the number of successful task completions, proportion of successful trials with a compensatory movement, and task completion times. Chi-square tests of independence implemented in the R-package *stats v3.6.2* (McHugh, 2013) were used to determine if the proportion of



		Description	Leading leg	Trailing leg
By leg(s)	Shuffle	Participant's foot is lifted off and down to the ground with a vertical displacement which is not associated with the actual stepping over motion.		
	Hover	Participant's foot is off the ground during the stepping over movement but showing a paused hovering motion.		
	Pivot	Participant's foot is rotated on the ground about the vertical axis of the shank. Part of the foot (e.g., heel or toe) can be lifted but not entirely off from the ground.		

		Description	One-handed	Two-handed
By hand(s)	Contact the wall	Participant contacts or braces against the wall with either the right or left hand or both hands together.		

Fig. 2. List, descriptions and example images of compensatory movement strategies involving use of one or both legs and hands used in the present study based on a preliminary video-based analysis (Lim et al., 2018).

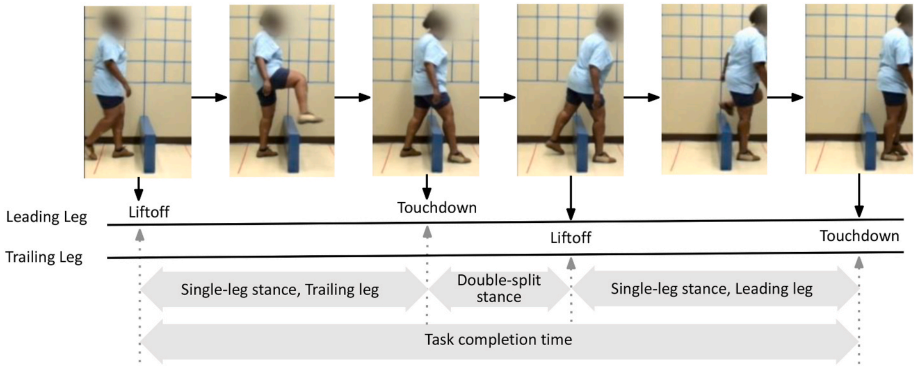


Fig. 3. Main gait events observed during one obstacle clearance trial (Lim et al., 2018) for the leading leg (right leg in this example) and trailing leg (left leg) with an obstacle height of 36 cm. Leading leg and trailing leg liftoffs and touchdowns were annotated in video-based observation analysis to calculate the duration of main gait events; namely, single-leg stance with the trailing leg, double-split stance, single-leg stance with the leading leg, and total task completion time.

successful trials differed significantly by obstacle height at a significance level of $p < .05$. Significant effects of obstacle height were examined using pairwise comparisons with Bonferroni-adjusted p-values at a significance level of $p < .05$. Correlations between the four time duration measures (i.e., single-leg stance with the trailing leg, double-split stance, single-leg stance with the leading leg, and total task completion time) were characterized using two-tailed Spearman's rank-order correlation coefficients at the $p < .05$ level (Spearman, 1987). Separate linear mixed-effects models implemented using the R package *lme4 v1.1- 27.1* (Bates et al., 2014) were used to quantify the effects of obstacle height, person variables (i.e., BMI, ABC score, RMSacc), and the type of compensatory movements used on each of the four time duration measures. Linear mixed effect models were considered since these allow both fixed and random effects, which is particularly useful when subsets of data are not independent and/or have a hierarchy or clusters. Including participant number as a random effect accounted for the repeated but unequal number of successful obstacle height conditions per participant. A step-wise variable selection procedure was used to obtain a parsimonious or reduced model with the largest explained variance for each measure of gait duration. The significance level for variable selection was set at $p < .05$. Residual errors from the reduced models were examined graphically and confirmed that model assumptions of multivariate normality were satisfied.

Study objective 2 associating obstacle height with the probability of successful task completion was addressed with multivariate Cox Proportional Hazards (PH) regression models using data from successful and failed trials ($n = 108$). Cox PH regression is commonly used in clinical research when associating one or more predictors (i.e., exposures or risk factors) to the probability or risk of experiencing an event of interest (e.g., fatality, injury), given that the participant has survived up to a specific time (Cox, 1972). The present study used Cox PH regression to quantify the strength of association between individual characteristics and use of compensatory movements on the probability of successful obstacle clearance – the event of interest, for a given normalized obstacle height, i.e., obstacle height expressed as percent stature. Normalized obstacle heights were used to account for between participant differences in stature and for converting the ordinal height values into a continuous variable yielding higher resolution to the outcome probabilities. The Cox PH model can be expressed as follows:

$$h(noh) = h_0(noh) \cdot \exp(b_1x_1 + b_2x_2 + \ldots + b_kx_k) \qquad (1)$$

where, *h(noh)* is the expected hazard for the normalized obstacle height "*noh*", $h_0(noh)$ is the baseline hazard and corresponds to the expected hazard when all predictors x_i are equal to zero, and the regression coefficients (b_1, b_2, …, b_k) quantify the strength of the association between each of the k predictors (x_1, x_2, …, x_k) and the outcome, i.e., the increase in the expected log of the relative hazard for each one unit increase in the predictor, holding other predictors constant. The quantity b_k in equation (1) is the hazard ratio (HR), and indicates whether the covariate has a positive association (if HR $>$ 1), no association (if HR $=$ 1), or a negative association (if HR $<$ 1) with the event probability.

Cox PH regression was chosen over other potential predictive models (e.g., logistic regression) due to its ability to model right-censored data since successful trials were capped at the 66 cm obstacle height, while also examining associations with continuous and categorical between-subject variables. Three incremental PH models were tested and compared examining associations of the outcome with (i) BMI alone, (ii) BMI and standing balance (ABC score, RMSacc), and (iii) BMI, ABC score, RMSacc, and the type of compensatory movement used. The Cox regression models were implemented in R using the *Survival package v3.2-11* and *survminer package v0.4.9* (Therneau and Grambsch, 2000; Therneau et al., 2015). Goodness-of-fit for the three regression models were assessed using the R-squared and concordance statistic. Model results were presented as the parameter estimates for each predictor, their hazard ratios (95% CI) obtained by exponentiating the parameter estimates, and significance at the level of $p < .05$. The relationship between normalized obstacle height, statistically significant predictors and the probability of success (outcome) were also plotted graphically (Therneau and Grambsch, 2000). The notation '*N*' in the Results section refers to participant counts and '*n*' to trial counts, respectively.

3. Results

Statistics on the study sample are summarized in Table 1. Other than for stature wherein men were significantly taller compared to women [t (1, 16) $= -4.1$, $p < .001$], none of the other person variables differed significantly by gender. Hence subsequent statistical analyses were performed on the pooled sample. Based on anthropometry, tested obstacle heights were equivalent to 21–39% of the participant's stature. The normalized obstacle heights (% stature) had a mean ± S.D. of 21.3 ± 1.2% (range: 19.4–23.5%) at the lowest height condition of 36 cm, and 39.0 ± 2.1% (range: 35.6–43.1%) at the highest obstacle height of 66 cm.

Eleven participants successfully cleared all seven obstacle heights, whereas the remaining 7 participants were unsuccessful at one of the intermediate heights and hence did not complete all seven trials. Thus, of the 126 maximum possible number of trials (i.e., 7 obstacle heights × 18 participants), 108 task trials (101 successful vs. 7 unsuccessful trials) were conducted and analyzed. In terms of approach direction, the majority of participants opted for an anterior facing approach ($n = 82$ of 108 trials; 75.9%) over a lateral side-step approach ($n = 26$ of 108 trials; 24.1%). The anterior-facing approach was used in 78.2% ($n = 79$ of 101) of the successful trials, and 71.4% ($n = 5$ of 7) of the unsuccessful trials.

3.1. Successful task completions by Obstacle height and compensatory movements

Fig. 4 presents a bar graph with the proportion of successful task completions (%) at each obstacle height (cm), along with the frequency count of successful trials with vs. without any type of observed compensatory movement. The proportion of successful task completions gradually declined from 100% ($N = 18$ of 18 participants) at the two lowest obstacle heights of 36 cm and 41 cm down to 66.1% ($N = 11$ of 18 participants) at the two highest heights of 61 cm and 66 cm, respectively; however, the decreasing trend was not statistically significant ($\chi^2 = 4.87$; $p = .561$).

A correlation analysis was performed to understand whether the maximum height completion accounted for participants' stature. The coefficient of determination between the maximum obstacle height completed by each participant versus their stature was low with an R^2 of .023, and the data showed no positive or negative correlation trend between them (more details in the supplementary data). Thus, there seemed to be no potential link between participant stature and success rate.

A total of 54 compensatory movements across 41 of the 101 successful trials were identified. Within each obstacle height the frequency counts were not mutually exclusive since more than one compensatory movement could be used during a trial. Compensatory movements were observed in 3–4 trials at the three lowest heights, increasing to 10 of 11

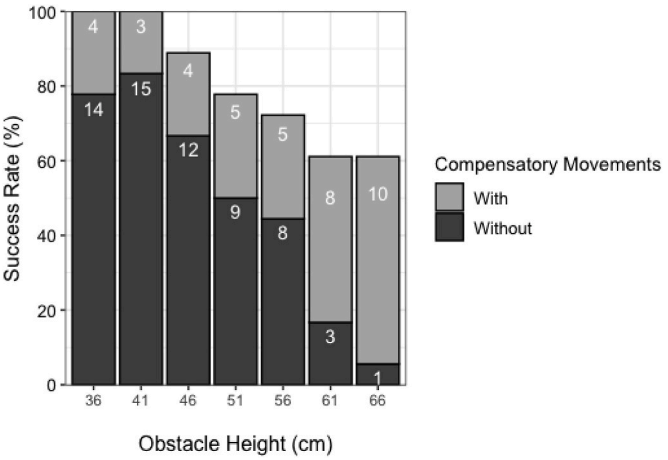


Fig. 4. Bar graph depicting success rates (%) across obstacle heights (cm) computed as the proportion of successful trials out of all participants ($N = 18$). Numbers in each bar represent the number of successful trials either with (gray) vs. without (black) use of any compensatory movements involving the leg(s) and/or hand(s).

Table 1
Mean ± S.D., and ranges (min, max) for the person variables ($N = 18$) stratified and compared by gender. An asterisk (*) indicates a significant difference in gender at $p < .05$.

	Men ($N = 9$)		Women ($N = 9$)		Total ($N = 18$)	
	Mean ± S.D.	Range	Mean ± S.D.	Range	Mean ± S.D.	Range
Age (years)	50.2 ± 10.2	33, 67	49.3 ± 10.2	30, 63	51.1 ± 10.7	30, 67
Stature (mm)*	1760 ± 69.3	1661, 1853	1631 ± 63.0	1530, 1758	1695 ± 92.3	1530, 1853
Body mass (kg)	121.3 ± 29.0	86.4, 171.9	102.3 ± 17.9	74.2, 132.9	111.8 ± 25.4	74.2, 171.9
BMI (kg/m^2)	38.9 ± 7.8	30.2, 51.4	38.2 ± 4.8	31.7, 45.6	38.6 ± 6.3	30.2, 51.4
Waist-to-stature ratio	0.69 ± 0.09	0.58, 0.87	0.72 ± 0.08	0.60, 0.85	0.71 ± 0.08	0.58, 0.87
ABC score (0–100%)	92.0 ± 10.5	73.8, 100	90.3 ± 11.0	62.5, 98.1	90.7 ± 10.4	62.5, 100
RMSacc (g)	0.07 ± 0.03	0.02, 0.10	0.07 ± 0.02	0.03, 0.09	0.07 ± 0.02	0.02, 0.10

trials at the maximum obstacle height of 66 cm. Only one participant (stature: 1.8 m, BMI: 31.8 kg/m^2) successfully cleared the maximum obstacle height without using a compensatory movement. The three most frequently used compensatory movements were the use of one or both hands for bracing ($n = 24$), a pivot motion of the stance foot while clearing the obstacle ($n = 18$; 7 leading vs. 16 trailing leg vs. 5 both legs), and hovering of the leg during the swing phase to maintain/regain stability ($n = 12$; 9 leading vs. 3 trailing leg). The leg pivot motion during single-leg stance with the trailing leg involved an external tibial rotation as participants turned from an anterior to lateral approach to face the wall and swing the leading leg over the obstacle; conversely, the pivot motion during single-leg stance on the leading leg involved internal tibial rotation to swing the trailing leg over the obstacle while also turning away from the wall. Hand bracing occurred concurrently with the leg pivot motion in 66.5% of the successful trials at the highest obstacle height (66 cm), and in 55.6% of successful trials at all other heights. Shuffling of the feet was observed only once at the 41 cm height, and hence was excluded from subsequent analysis.

Fig. 5 depicts the proportion of successful trials for each obstacle height stratified by the type of compensatory movement used, namely, leg hover, pivot, hand contact, and a combined category representing any one or more of the movements. The proportion of successful trials that involved use of any one or more compensatory strategy increased significantly with obstacle height ($\chi^2 = 28.48$, $p < .001$). Post hoc paired comparisons indicated a significantly higher proportion of compensatory movements used at obstacle heights of 66 cm compared to 36 cm ($p = .007$), 41 cm ($p < .001$), 46 cm ($p = .007$), and 51 cm ($p = .046$), respectively. Chi-square tests by type of compensatory movement indicated significant associations between obstacle height and leg hover movements ($\chi^2 = 20.61$, $p = .002$), leg pivot ($\chi^2 = 16.16$, $p = .013$), and hand use ($\chi^2 = 13.12$, $p = .041$); however, these tests were less reliable due to the low cell proportions for some obstacle heights and hence post hoc tests were not performed.

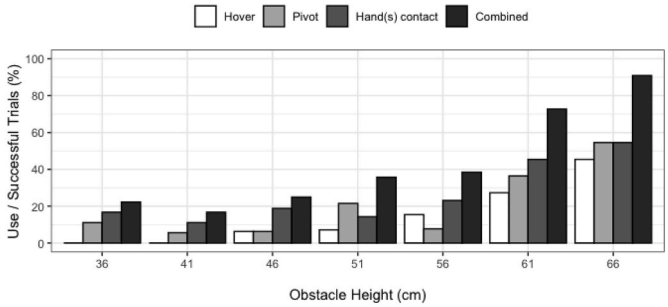


Fig. 5. Bar graph depicting the proportion (%) of successful trials by obstacle height stratified by type of compensatory movement used, namely, either a leg hover or pivot motion or use of the hand(s) for bracing vs. any one or more of the three movements combined.

3.2. *Task completion times*

Box plots for each gait duration by obstacle height are presented in Fig. 6. The overall task completion times were relatively short, ranging between 1.5 s and 4 s, and increased with obstacle height from a median value of 1.9 s at 36 cm to 2.7 s at 66 cm. Box plots for the three gait phases provide an indication of the contributors to this increase. Both, single-leg stance duration for the trailing leg and leading leg increased with obstacle height (i.e., a 0.5 s median increase from 36 cm to 66 cm), while median double stance duration marginally decreased with increasing obstacle height (i.e., a 0.1 s median decrease from 36 cm to 66 cm). Non-parametric Spearman's rank-order correlations indicated significant positive correlations between task completion time and single leg stance duration for the trailing leg ($\rho = 0.87$, $p < .001$) and leading leg ($\rho = 0.87$, $p < .001$), respectively, but not with double-stance duration ($\rho < 0.001$, $p = .996$). Single-leg stance duration between the trailing and leading legs were also highly correlated ($\rho = 0.60$, $p < .001$) with each other, though not with double-stance duration.

Linear mixed-effects models were used to test for associations between gait phase duration and obstacle height, while adjusting for person variables (continuous) and type of compensatory movements (binary). Results from the reduced linear mixed-effects models are summarized in Table 2. Obstacle height was significantly associated with all four measures of gait duration. Single-leg stance duration for the trailing leg increased significantly with increasing obstacle height ($F = 6.48$, $p < .001$), use of leg hover motions ($F = 2.75$, $p = .007$), and hand contact for bracing ($F = 2.30$, $p = .024$). Double stance duration decreased significantly with increasing obstacle height ($F = -5.50$, $p < .001$), however none of the other variables were statistically significant. Single-leg stance duration for the leading leg increased significantly with increasing obstacle height ($F = 7.63$, $p < .001$), greater RMSacc, i.e., worse standing balance ($F = 2.37$, $p = .032$), and use of hand contact ($F = 4.52$, $p < .001$), though notably decreased when a pivot movement was used ($F = -2.02$, $p = .047$). Overall task completion time increased significantly with increasing obstacle height ($F = 7.43$, $p < .001$), use of leg hover motions ($F = 2.07$, $p = .041$), hand contact ($F = 3.46$, $p < .001$), and significantly decreased with greater ABC scores, i.e., better balance ($F = -2.36$, $p = .031$).

3.3. *Probability of success*

Table 3 provides the parameter estimates, hazard ratios (95% CI), and *p*-values from three sequential Cox PH regression models examining the expected hazard, i.e., probability of successful vs. failed obstacle clearance at normalized obstacle heights associated with BMI alone (unadjusted Model–1), BMI adjusting for standing balance (Model–2), and adjusting for standing balance and use of compensatory movements (Model–3).

Cox PH regression indicated a significant association between BMI and the expected hazard, with a one unit (kg/m^2) increase in BMI associated with a 14%, 23% and 14% increase in the expected hazard across the three models, respectively. Compared to Model–1, adjusting for standing balance in Model–2 did not yield any significant improvement in model fit ($R^2 = 0.33$ vs. 0.31; $\chi^2 = 1.17$, $p = .557$). However, adjusting for compensatory movements and standing balance in Model–3 produced a significant improvement in goodness of fit ($R^2 = 0.53$; $C = 0.75$) compared to both, Model–1 ($\chi^2 = 14.39$, $p = .013$) and Model–2 ($\chi^2 = 13.22$, $p = .004$), respectively. Notably, in Model–3, use of a pivot motion was associated with a significant reduction in the estimated hazard by 70% (HR: 0.3, 95% CI: 0.09–0.96) indicating a protective effect compared to when a pivot motion was not used.

Fig. 7 provides a graphical depiction of the significant associations in Model–3, namely, the effects of BMI and use of a leg pivot motion on the probability of a successful obstacle clearance at normalized obstacle heights ranging from 19.4% to 43.1%, holding other predictors constant. Fig. 7A demonstrates the estimated probability of success for all participants ($N = 18$) tested in this study at mean values for the covariates. This estimation was split into three BMI categories in Fig. 7B based on the NIH classification of obesity severity (National Institutes of Health, 1998) to convey the effect of BMI on the probability of successful obstacle clearance. The probability of success showed a marked decrease as obesity severity increased from class I ($30 <$ BMI <35 kg/m^2) to class III (BMI >40 kg/m^2). Lastly, Fig. 7C depicts the increase in probability of successful obstacle clearance associated with vs. without use of a leg pivot motion as a compensatory movement.

4. Discussion

This study quantified the relationship between obstacle height and excess body mass on performance in an obstacle clearance task. Task

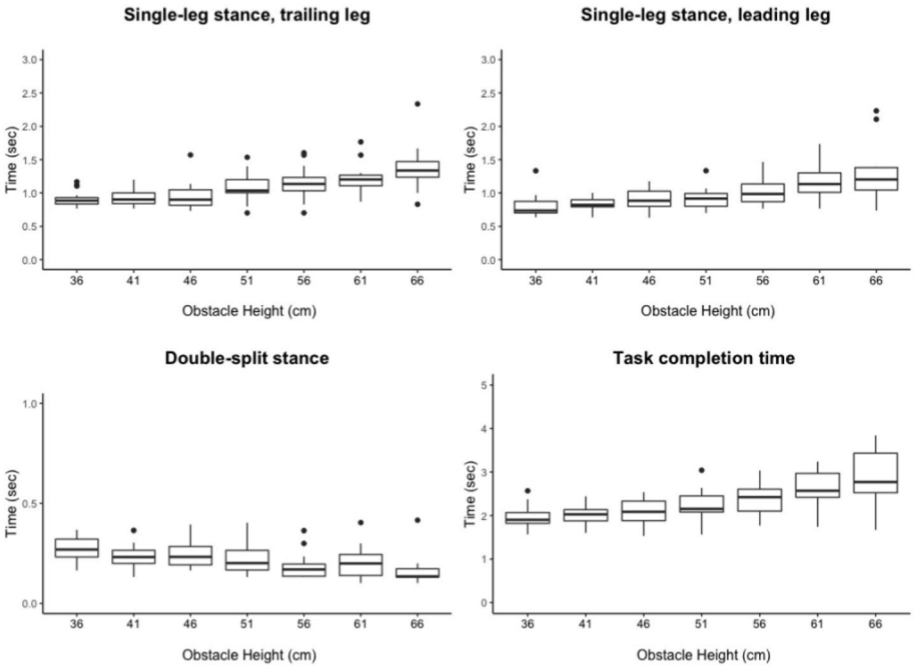


Fig. 6. Box plots of main gait duration (seconds) for successful trials at each obstacle height (cm). Dots indicate statistical outliers [i.e., values outside the range (Q1–1.5 × IQR, Q3 + 1.5 × IQR)].

Table 2

Summary results from the reduced linear mixed-effects regression models examining the effects of obstacle height, BMI, ABC score, RMSacc, and use of compensatory movements (hover, pivot, hand(s) on wall) on four gait event durations. Values in bold indicate significant effects at $p < .05$.

	Completion times											
Parameter	Single leg stance, trailing leg			Double split stance			Single leg stance, leading leg			Total Task completion		
	Estimate (SE)	d.f.	F, *p*-value	Estimate (SE)	d.f.	F, *p*-value	Estimate (SE)	d.f.	F, *p*-value	Estimate (SE)	d.f.	*p*-value
Intercept	0.60 (0.11)	1,97	5.67, **< .001**	0.35 (0.03)	1, 84	13.37, **< .001**	0.07 (0.14)	1,47	0.49, .625	2.46 (0.50)	1,19	4.91, **< .001**
Obstacle height (cm)	0.01 (0.01)	1,88	6.48, **< .001**	−0.01 (0.01)	1, 85	−5.50, **< .001**	0.01 (0.01)	1,96	7.63, **< .001**	0.02 (0.01)	1,91	7.43, **< .001**
BMI (kg/m^2)	–	–	–	–	–	–	–	–	–	–	–	
ABC (score: 0–100)	–	–	–	–	–	–	–	–		−0.01 (0.01)	1,16	−2.36, **.031**
RMSacc (g)	–	–	–	–	–	–	2.95 (1.24)	1,14	2.37, **.032**	–	–	–
Hover	0.17 (0.01)	1,94	2.75, **.007**	–	–	–	–	–	–	0.22 (0.10)	1,96	2.07, **.041**
Pivot	–	–	–	–	–	–	−0.12 (0.06)	1,90	−2.02, **.047**	–	–	–
Hand(s) on wall	0.12 (0.05)	1,96	2.30, **.024**	–	–	–	0.25 (0.06)	1,76	4.52, **< .001**	0.30 (0.09)	1,87	3.46, **< .001**

performance was operationalized as the maximum obstacle height cleared, four duration measures of successful task completion, and compensatory movements used during task completion. Higher obstacle heights were associated with significantly fewer task completions, longer duration of leading and trailing leg stance and overall task completion, and more frequent use of compensatory movements for successful obstacle clearance. BMI was not associated with the longer duration of leading and trailing leg stance and overall task completion after adjusting for standing balance and use of compensatory movement. The probability of successful task completion significantly decreased with increasing BMI, and increased with use of a leg pivot motion during task completion, after adjusting for standing balance and other types of compensatory movements.

4.1. *Effects of Obstacle height*

The overall findings from this study support the notion that increasing obstacle height inherently increased the demands on postural stability. This was evident from the significantly fewer task completions, the small but statistically significant increases in single leg stance duration for the trailing leg and leading leg and overall task completion time, and an increasing use of compensatory movements with increasing obstacle height. Increasing obstacle height would require greater vertical displacement of the leading leg, a longer single-leg support time and consequently more active hip abduction about the supporting leg, which would inadvertently increase postural instability (Stegemöller et al., 2012). Maintaining stability while standing on one leg with the other leg in dynamic transition (e.g., swinging over the obstacle) also increases the demand on the sensorimotor system particularly proprioceptive feedback. Specifically in the case of individuals with excess body mass,

Table 3
Hazard ratio (95% CI) per risk factor from the multivariate Cox PH models for the normalized obstacle height (obstacle height/stature × 100%). Values in bold indicate significant effects at $p < .05$. HR > 1: a positive association between the covariate and the event probability, HR = 1: no effect, HR < 1: a negative association.

	Model-1: BMI			Model-2: BMI + balance measures			Model-3: BMI + balance measures + comp movements		
	Estimate	HR (95% CI)	P-value	Estimate	HR (95% CI)	P-value	Estimate	HR (95% CI)	P-value
BMI (kg/m^2)	0.135	1.14 (1.07, 1.22)	**< .001**	0.208	1.23 (1.00, 1.51)	**.049**	0.132	1.14 (1.05, 1.25)	**.003**
ABC (score: 0–100)	–	–	–	−0.047	0.95 (0.86, 1.06)	.368	−0.013	0.99 (0.94, 1.03)	.559
RMSacc (g)	–	–	–	−0.171	0.84 (0.33, 2.16)	.823	−0.195	0.82 (0.35, 1.95)	.658
Hover (yes vs. no)	–	–	–	–	–	–	−0.957	0.38 (0.06, 2.48)	.315
Pivot (yes vs. no)	–	–	–	–	–	–	−1.208	0.30 (0.09, 0.96)	**.043**
Hand (yes vs. no)	–	–	–	–	–	–	−0.304	0.30 (0.16, 2.60)	.614
Model Goodness-of-fit									
Coefficient of determination (R^2)		.31			.33			.53	
Concordance (C)		.70			.70			.75	

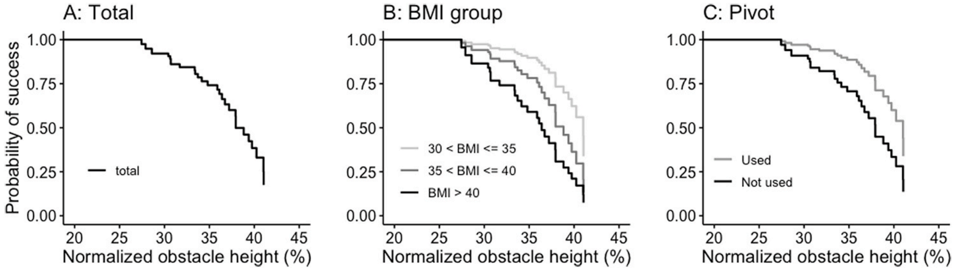


Fig. 7. Estimated probability of successful obstacle clearance for obstacle heights normalized to stature based on the results of the Cox PH Model–3, (A) across all trials (n = 108), (B) for three BMI classes, and (C) with vs. without use of a pivot motion.

the increased postural instability and fall risk in single leg stance stems from the rationale that the altered centre of mass position relative to the ankle joint among individuals with excess body mass (particularly in the trunk and/or abdominal area) requires ankle torque to be generated more rapidly and of higher magnitude in order to maintain and/or regain stability (Hue et al., 2007; Corbeil et al., 2001). The seven obstacle heights between 31 cm and 66 cm used in this study ranged from slightly below knee height (~20–25%) to close to hip height (~40–45%) for most participants in a relative sense. Some of these heights were higher and thus more challenging than heights used in prior studies that also used an obstacle clearance paradigm for studying postural stability, e.g., 36 cm maximum used by Azevedo (2014), 16 cm maximum by Gill and Hung (2012), and 10 cm maximum by Houser et al. (2008).

4.2. *Effects of excess body mass*

The relationship between BMI and task performance was more pronounced in the probability of successful obstacle clearance and use of compensatory movements, compared to task duration. BMI was not significantly associated with any of the four task duration measures after accounting for standing balance and use of compensatory movements. The fact that participants used different compensatory movements to maintain stability during both stance phases would have invariably altered the task duration. It is also worth noting that although BMI was not statistically associated with task duration does not imply that BMI was unimportant, but rather that BMI accounted for a lesser proportion of the unique variance in task duration compared to standing balance and use of compensatory movements and thus was less consequential in the process of variable selection. Regardless, the within-participant differences in task times were very small, a few seconds or less across obstacle heights and other significant factors, and thus of potentially less practical value.

The study modeled the relationship between probability of successful vs. failed obstacle clearance and normalized obstacle height using Cox PH regression and included BMI, standing balance, and three different compensatory movements, namely, hover and pivot motions involving the leg and use of one or both hands for bracing as covariates. The notable performance outcome associated with BMI was the significantly lower probability of successful task completion with higher BMI. The Cox PH model also found that a leg pivot movement was associated with a significantly higher probability of successful task completion, after adjusting for BMI, standing balance, leg hover and hand use. The ability to perform and recruit these pivot movements in a timely manner may moderate task performance (efficiency and safety).

A novel aspect of this study was the emphasis on compensatory movements adopted during the task for maintaining and/or regaining stability. Findings from the video-based analysis indicated that only three of the four types of compensatory movements initially described were frequently used. Compensatory movements involving the legs included a hovering motion of the leg when moving over the obstacle, and a pivot motion that involved internal or external rotation about the stance leg to turn either toward (pivoting the trailing leg) or away from (pivoting the leading leg) the wall. Both of these movements reflect an internal stabilization mechanism. The use of one or both hands for bracing against the wall reflect an external stabilization, analogous to use of a grab-bar or handrail. This study intentionally avoided presenting any assistive feature such as grab-bars or handrails in order to avoid a potential priming effect. The mere presence of an assistive feature within reach distance could potentially cue participants to proactively select or react with certain movements for stabilization (Ghafouri et al., 2004). The absence of any grab-bars or handrails in the present experimental set-up implies that these compensatory movements elicted were naturally selected in real-time from among different sensorimotor control strategies (and not cued or primed) in order to help achieve the higher-level task goal. While still an exploratory study, these findings suggest that the ability to recruit different internal and/or external stabilization techniques, reflected in these compensatory movements, might offset the negative influence of high BMI on increased fall risk in obstacle clearance tasks and could potentially be the focus of training interventions for fall prevention.

4.3. Methodological considerations and limitations

From a methodological perspective, this study combined an ascending method of limits with an obstacle clearance paradigm to examine responses to increasing demands on postural stability. In other words, participants started the task without intending to use their hands for support, then realized the task demands exceeded their capabilities, and so modified their initial motor planning to accommodate the demands. Discrepancy in judgment during motor planning for daily activities is less effective in older adults (Maki and McIlroy, 2006) and known to increase fall risk (Segev-Jacubovski et al., 2011). Our study found leg pivoting in a single-leg stance to be a movement strategy that improved obstacle clearance performance, but in fact, it can be a potential fall hazard if combined with environmental factors such as a slippery surface in practice. Thus, ideally, proper assistive features (e.g., grab bars) aiding safe hand support are needed while the trailing leg can pivot to promote the successful clearance of the leading leg (Ghafouri et al., 2004).

Due to its exploratory nature, this study had a limited sample size ($N = 18$). In addition, this study did not include a control group (BMI $<$30 kg/m^2) for comparison; an investigation into whether people with high BMI use different compensatory strategies on high obstacle clearance tasks compared to a control was beyond the scope of this study. However, the study sample had a broad range in BMI, i.e., between 30 and 51 kg/m^2, and was relatively healthy with no other severe impairments related to ambulation, vision or standing balance. As such, the sample could be considered to have a low to moderate fall risk. However, using a method of limits allowed for multiple measurements per participant particularly to understand their change in movement patterns and stabilization technique with increasing task demand. Based on a sample size calculation following the method described in Chow et al. (2017), the total sample size of 95 would be needed to ensure a power of .8 and a type I error rate of no more than 10% in the Cox PH model when using the covariate “pivot” in the calculation. Our sample size ($n = 108$) was greater than the calculated sample size, confirming that the sample size was sufficient.

The present study opted for obstacle heights in 5 cm (∼2 in) increments with participants presented with each obstacle height only once and in ascending order. This was done to keep the number of trials few and manageable (i.e., seven) in order to establish a suitable range in terms of task difficulty and completion percentage. Based on the performance measures described, this height range was successful in eliciting sufficient diversity in performance, specifically, success rates, task completion times, and compensatory movements in a relatively time- and cost-efficient manner and with sufficient detail for statistical analyses that addressed the study objectives. While still being exploratory, this method could potentially be used to rapidly assess postural stability and fall risk in research and clinical settings in populations with a low to moderate fall risk. Subsequent studies could potentially use smaller height increments and with multiple repetitions. Including repetitive measures of static balance (RMSacc) would also be beneficial in understanding if/how variability between repetitions in a static balance measure might be associated with dynamic balance performance. Similarly, multiple repetitions on obstacle clearance task trials at each height would allow investigation of the variability in performance and potential changes in movement strategy with additional practice and adaptation. Also, allowing participants to freely select a preferred approach side and leading leg each time will provide insights into whether different postural adjustments are adopted over time with increasing obstacle height. However, these additions represent a trade-off in terms of number of trials, fatigue, and learning effects. The use of more objective instrumentation-based measures, such as inertial measurement units (IMUs) or optical motion capture, could further help investigate transient dynamic balance and postural control during obstacle clearance (Kong et al., 2014).

This study was conducted under ideal laboratory conditions on a dry floor and did not simulate conditions such as wet or slippery flooring. In addition, we provided enough clearance space before and after the obstacle (2 m each), which allowed participants to take two or more steps before and after clearing the obstacle for safety reasons. As such the present study conditions reflected a potential best-case scenario or ceiling effect on performance. Adding real-world fidelity to the setup in terms of wet or slippery flooring, as well as a tight clearance space, would potentially lower rates of task completion and/or longer task completion times and more frequent use of stabilization techniques as participants would adopt a more cautious approach. The addition of handrails and grabbars could also have altered the study findings, however, the specific location, orientation and profile design (profile, hand clearance, etc.) of these assistive features introduce a range of different variables whose effects on postural stability and fall prevention remains a topic of active research (Levine et al., 2021).

Unlike the present study that used task success as the outcome, prior studies that developed statistical models for obstacle clearance tasks have used either temporal or spatial measures (e.g., toe clearance) as a proxy for fall risk (Duhamel et al., 2004; Garman et al., 2015; Amatachaya et al., 2015; Uemura et al., 2011). One reason for this approach in prior studies was their relatively low obstacle height and hence little to no instances of obstacle collision or fall. For example, Garman et al. (2015) used a bootstrapping technique to model the probability of tripping as a function of obstacle height using the minimum vertical foot clearance from the obstacle as the outcome. While the obstacle height was set at 7 cm, stepping over similar obstacles repeatedly and by multiple individuals allowed for examining effects of age, obesity, gender, and gait speed (Garman et al., 2015). The probability of tripping was found to be higher among older adults, obese adults, females, and at a slower self-selected speed (Garman et al., 2015). Other studies have used logistic regression to model fall risk in simulated obstacle clearance tasks with clinical populations, such as older adults (Uemura et al., 2011) and individuals with spinal cord injuries (Amatachaya et al., 2015).

The use of the Cox PH model in this study directly determines the probability of success in clearing obstacles as a function of obstacle height. The Cox PH model was helpful in building such a predictive model, especially because a measured individual’s maximum obstacle height might not be their *true* maximum, as the study only investigated obstacle heights up to 66 cm for safety and practical reasons. Considering that 61.1% (11 of 18) participants successfully cleared the given maximum obstacle height (66 cm), there was a ceiling effect in the observed data. Unlike other statistical inference methods, such as logistic regression (Wright, 1995), which does not consider the time of the observation in probability estimation (for which the obstacle height is a proxy in our case), the Cox PH model allows time-to-event analysis by considering information about both, success (successful completion or not) and the obstacle height in calculating probabilities. In other words, the Cox PH model allowed us to build a predictive model that accommodates both censored (successful up to the maximum height tested) and non-censored (failed) data (Kumar and Klefsjö, 1994).

4.4. Implications for design

Commercial bathtubs in the US have a broad height range from 35 cm (14 in) to 51 cm (20 in), with a standard bathtub height being 46 cm (18 in). A 41 cm (16.1 in) obstacle height was the maximum height that all participants in this study could successfully clear, either with (16.7%) or without (83.3%) use of any compensatory movement. Obstacle heights above this value resulted in less than perfect completion percentages. From the Cox PH model results depicted in Fig. 7A, the normalized obstacle height where 95% of the population with obesity could succeed was 27.9% of the average stature, which is equivalent to 47.3 cm (18.6 in). This is slightly above the standard bathtub height, but lower than the maximum height range (51 cm; 20 in) implying potential fall risks associated with current commercial bathtub designs for high-BMI individuals. For highly obese individuals (BMI >40 kg/m^2), this reduces to 27.5% (46.5 cm; 18.3 in), which is at about a standard bathtub height.

The 1990 Americans with Disabilities Act (ADA) guidelines does not offer specific bathtub height recommendations, but it does indicate that the top of bathtub seats shall be 43–48 cm (17–19″), which is at about the same height as, or slightly higher than, the height of the rim of the bathtub [Fig. 610.2 in Department of Justice (2010)]. This ADA-recommended height is still slightly greater than the 95% accommodation level for individuals with obesity. Furthermore, under the current ADA guideline and following a 2021 opinion of the US Court of Appeals for the Seventh Circuit, extreme obesity is not considered an actionable impairment unless caused by an underlying physiological disorder or condition(Wallin, 2021). Thus, there may be need for revisiting the accessible design standards and guidelines for high obstacles commonly encountered in ADLs, such as bathtubs, to accommodate the growing population of individuals with obesity.

5. Conclusions

This study combined an ascending method of limits with an obstacle clearance paradigm to quantify obstacle clearance performance as an indicator of fall risk in individuals with high BMI. Increasing obstacle height was associated with increasing demands on postural stability, reflected in the significantly lower percentages of successful task completion, longer single-leg stance duration for both the leading and trailing leg and overall task completion, and more frequent use of compensatory movements reflecting internal and external stabilization techniques for successful obstacle clearance. Although BMI was not associated with task duration, better standing balance and use of compensatory movements were associated with shorter task duration. Notably, higher BMI was associated with a significantly lower probability of successful task completion, even after adjusting for measures of standing balance and use of compensatory movements.

Another key finding related to high BMI and fall risk was the frequent use of different compensatory movements for maintaining/regaining stability and its potentially protective effect on fall risk, i.e., increased probability of successful obstacle clearance. Though increasing BMI lowered the probability of successful obstacle clearance, the ability to recruit different internal and external stabilization techniques may compensate for or ameliorate the negative effects of excess body mass on postural instability and fall risk in obstacle clearance tasks. While confirmatory studies with a larger sample are needed, findings from this initial study suggest that the real-time recruitment of internal and external stabilization techniques could potentially serve as a clinical indicator of reduced fall risk and be the focus of fall prevention interventions. In addition, the study method used was successful in eliciting key postural responses and behaviors in a relatively time- and cost-efficient manner and with sufficient detail to model these relationships. Although exploratory, this method could potentially be used to rapidly assess postural stability and fall risk in research and clinical settings in populations with a low to moderate fall risk.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2022.103879.

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