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Original Article

The impact of weight classification on safety: timing steps to adapt to external constraints

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Abstract

Objectives: The purpose of the current study was to evaluate how weight classification influences safety by examining adults' ability to meet a timing constraint: walking to the pace of an audio metronome. **Methods:** With a cross-sectional design, walking parameters were collected as 55 adults with normal (n=30) and overweight (n=25) body mass index scores walked to slow, normal, and fast audio metronome paces. **Results:** Between group comparisons showed that at the fast pace, those with overweight body mass index (BMI) had longer double limb support and stance times and slower cadences than the normal weight group (all *ps*<0.05). Examinations of participants' ability to meet the metronome paces revealed that participants who were overweight had higher cadences at the slow and fast paces (all *ps*<0.05). **Conclusions:** Findings suggest that those with overweight BMI alter their gait to maintain biomechanical stability. Understanding how excess weight influences gait adaptation can inform interventions to improve safety for individuals with obesity.

Keywords: Overweight, Body Mass Index, Adaptation, Safety

Introduction

The prevalence of overweight among adults in the United States is high[1,2]; 68% of U.S. adults over 20 years old are currently overweight[3]. Classifications of overweight are derived from measures of body mass index (BMI) scores (i.e. weight in kg/height in m^2)[4]. BMI scores ≥25 kg/m^2 and <30 kg/m^2 are categorized as overweight[3].

Weight classification influences motor skill; being overweight affects walking[5-7], motor coordination[8] and balance[9]. Observations of regular, over-ground walking in individuals who are overweight show a decrease in cadence (steps/minute)[10] and a decrease in step[10] and stride length[11,12] and in step frequency[13] compared to those with normal BMI scores. Other differences involve walking more slowly by decreasing overall velocity[10-12] and maintaining contact with the ground for longer periods of time by decreasing swing time[10] and by increasing double limb support time[11] and stance time[10,11]. Motor coordination patterns in individuals with higher BMI scores are more variable than those with normal BMI; individuals with obese BMI scores demonstrate higher stride-to-stride intra-subject variability with interjoint coupling parameters compared to those with normal weight[8]. Excess mass also affects adults' ability to perform tasks that require controlling the center of mass. For example, adults with obese BMI exhibit poorer sit-to-stand performance via decreased peak and mean vertical sacrum velocity[14,15] and decreased maximum strength as measured by 1-RM bench press and squat exercises[16]. Increased BMI also disrupts balance, which is reflected by increased postural sway[9,17] and decreased scores on balance tests[18].

Obesity has an effect on walking biomechanics and bioenergetics. Adults with overweight and obese BMI exhibit reduced range of motion at the ankle, knee, and hip during walking[19]. They also demonstrate greater absolute ground reaction forces[20] and increased load at the knee[21] when walking faster than their preferred speed compared to normal weight adults. Obesity also increases the energy cost of walking when

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BMI Group	Age (years)	Weight (kg)	Height (cm)	BMI (kg/m²)	Leg length (cm)	Sex
Normal weight	26.33 (8.42)	56.84 (4.73)	161.77 (4.05)	22.52 (1.68)	85.68 (4.03)	24F, 6M
Overweight	26.49 (5.11)	70.87 (4.06)	165.13 (4.24)	26.60 (1.11)	89.38 (3.52)	17F, 8M
*Note that for Sex that F=female and that M=male.						

Table 1. Demographic information. Means are listed with standard deviations in parentheses.

walking at different, imposed stride frequencies[22]. These gait differences, particularly slower preferred walking speeds, can be attributed to an attempt to increase stability[23], to minimize mechanical external work[24], to decrease load at the knee[25], and to curb energy cost and relative effort[20].

Differences in walking and balance can increase safety risks (i.e. falls and injuries incurred from falling) for individuals who are overweight[9,26,27]. Adults who are overweight are 15-48% more likely to sustain injuries requiring medical attention[28] and report falling twice as often as normal weight adults[29]. This impacts their ability to safely engage in activities that require adapting their motor actions to meet timing or accuracy constraints[27]. Walking requires timing steps appropriately to maintain safety. For instance, studies on falls with the elderly show that deficits in timing steps appropriately often leads to an inability to recover from loss of balance to prevent falling[30]. Often, attempts to meet timing constraints result in sacrificing accuracy to prevent falling or in meeting the constraint at the risk of falling[31]. Similarly, studies examining the effects of obesity on walking at different speeds shows that adults with obese BMI scores walk with greater knee joint loads[20], slightly elevated net metabolic rates[32,33], and greater force requirements in the gluteus medius, gastrocnemius, and soleus muscles[34].

Although body weight and difficulty meeting timing constraints increase safety risks for overweight individuals, little research has examined how to quantify adaptation to minimize safety risks in the overweight population. Instead, most interventions to address safety risks are geared towards elderly or neurologically impaired populations. For example, training older adults to appropriately time their steps when walking helps them to recover balance before falling[35]. Repetitive step training in which prompts are used to encourage participants to time their steps to cues has been shown to improve the timing of steps[36]. However, this has only been attempted with the elderly[30] and with individuals with Parkinson's disease[37].

The aim of this study was to evaluate how weight classification relates to an important aspect of maintaining safety while moving: the ability to meet a timing constraint (i.e. walking to the pace of an audio metronome). The study focused on adults with normal and overweight BMI scores who attempted to match their walking to the pace of an audio metronome. Three main questions guided this research: 1) Would weight classification affect participants' ability to adapt their walking to the metronome pace? 2) How would walking during the metronome compare to normal baseline walking? 3) Since walking parameters differ for individuals who are overweight, might they sacrifice accuracy for biomechanical stability or maintain accuracy and sacrifice biomechanical stability?

Methods

Participants

Table 1 shows participants' demographics. A total of 55 adults with normal (*n*=30) and overweight (*n*=25) BMI scores participated in the study in the *Motor Development Laboratory* at Boston University. As in previous gait studies[10,11] BMI was used as the main determinant of normal versus overweight status. Participants were recruited from Boston University via recruitment fliers. Participants were excluded if they were not between 18 and 60 years old, had significant injuries or medical conditions that prevented safe participation in the study such as cardiac, visual, hearing, and neuropathic conditions, and if their BMI was not greater than 19 kg/m^2 or less than 30 kg/m^2. The Boston University institutional review board approved the protocol.

Mechanized gait carpet and audio metronome

Spatial and temporal parameters of participants' footfalls were collected. A mechanized, pressure sensitive gait carpet (6.10 m long x 0.89 m wide) registered the x and y coordinates of every footfall in real-time with a 0.64 cm spatial resolution (GAITRite Inc., Clifton, New Jersey, http://www.gaitrite.com) at 120 Hz. GAITRite resident software was used to compute gait parameters. Specifically, using the GAITRite software, spatial and temporal parameters were computed with the x- and y-coordinates of the center of pressure for the heels and balls of the foot and the first and last times of participants' foot contacts respectively.

Two video cameras (Sony Corporation) recorded participants' walking movements for the entire session at 60 Hz; one camera captured a frontal view and the other captured a sagittal view of participants during the walking sequence. A third camera recorded a synchronization light attached to the gait carpet that signaled carpet activation. All camera views were mixed into a single view. With a frame-by-frame computerized video coding system (Openshapa.org), video recordings of sessions were used to synchronize walking sequences.

An audio metronome positioned approximately one meter away from participants provided an auditory cue. Three metronome paces were selected: normal, slow, and fast. The metronome paces in beats per minute (bpm) were chosen based on each adult's average cadence (steps per minute). Slow and fast paces were 25% lower and higher than the normal metronome pace.

Procedure

After participants provided informed consent, at the beginning of each session, their weights were obtained with a digital scale (American Weigh, americanweigh.com). A wand paired with the scale provided a digital reading of height when placed on participants' heads. Weight and height were used to calculate BMI in kg/m^2.

Participants' ability to alter their walking patterns to match an external task constraint, an auditory metronome, was assessed. Participants walked while shod under five experimental conditions. Ten trials were presented in each condition to ensure that consistent walking patterns were being observed. In the first condition, they walked across the gait carpet for ten trials at a self-selected pace to no metronome. Normal cadence was calculated by averaging cadences across the ten trials in condition one for each participant. In conditions two through four, they were asked to walk to the pace of the metronome at the normal, slow, and fast paces by making heel contact when hearing the beat. Slow and fast paces were individualized as 25% slower and faster than each participant's normal cadence. The three paces were counterbalanced for order across participants. During condition two, participants walked across the gait carpet to the pace of the metronome for ten trials. The condition was followed by two intermediate baseline trials in which participants walked across the carpet at a self-selected pace to no metronome. Conditions three and four were conducted similarly at the two remaining metronome paces. In condition five, participants walked across the carpet for ten last trials at a self-selected pace to no metronome. Participants were told that they could rest if needed during the course of the session.

Statistical analyses

All statistical analyses were completed using SPSS 20.0 statistical software (IBM). The results were presented as means (*M*) for all trials in each condition for each participant and standard deviations (*SD*) around those means. Dependent variables collected by the carpet were: cadence (steps/minute), step length (cm), stance time (msec), swing time (msec), double limb support time (msec), single limb support time (msec), and step time (msec). Data were analyzed for the right and left legs, but the results were identical. Therefore, the results reported are for the right leg only. Initial and final baseline comparisons between groups were compared with paired t-tests. Independent t-tests were used to assess between group differences at each metronome pace. Participants' ability to keep pace with the metronome was measured with one-sample tests for cadence and with paired t-tests for comparisons between step frequencies and cadence. To compare participants' walking at initial baseline to their walking at the metronome paces, 2 (BMI group) x 2 (initial baseline vs. metronome pace conditions) RM ANOVAs were conducted. For all tests, statistical significance was set at 0.05 (two-tailed). Bonferroni corrections were used to prevent experiment-wise errors.

	Normal BMI	Overweight BMI
Cadence (steps/min)	111.11 (6.95)	108.06 (7.45)
Step length (cm)	71.54 (5.83)	70.24 (5.81)
Swing time (msec)	408.30 (22.62)	411.32 (23.97)
Single support time (msec)	408.14 (22.51)	411.61 (23.80)
Double support time (msec)	263.41 (33.09)	286.73 (42.25)*
Step time (msec)	542.25 (34.57)	557.49 (39.70)
Stance time (msec)	671.52 (48.85)	700.50 (56.77)*
Velocity (m/sec)	1.32 (0.12)	1.27 (0.15)

Table 2A. Means and standard deviations from initial baseline.

	Normal BMI	Overweight BMI
Cadence (steps/min)	106.75 (8.47)	105.28 (9.17)
Step length (cm)	70.18 (5.93)	68.23 (6.44)
Swing time (msec)	420.89 (30.32)	415.82 (31.94)
Single support time (msec)	420.73 (30.30)	415.98 (31.69)
Double support time (msec)	284.42 (38.29)	310.28 (48.82)*
Step time (msec)	565.56 (45.58)	574.09 (50.30)
Stance time (msec)	706.85 (62.29)	730.56 (71.76)
Velocity (m/sec)	1.25 (0.14)	1.20 (0.17)
*NOTE: *=p<.05*		

Table 2B. Means and standard deviations from final baseline.

Results

Baseline comparisons

Tables 2A-B show the averages and standard deviations of initial and final baseline walking parameters for participants with normal and overweight BMI scores. At the initial baseline condition, there were no group differences in cadence, step length, swing time, single limb support time, step time, or velocity (all $ps>0.1$). However, participants who were overweight had higher double limb support times ($t(53)=-2.30$, $p<.05$, $d=-0.62$) and stance times ($t(53)=-2.04$, $p<.05$, $d=-0.55$) in comparison to normal weight participants. The results were similar for all parameters at the final baseline condition (all $ps>0.1$) with the exception of double limb support time. Like the initial baseline condition, the group with overweight BMI scores had higher double support times than the normal weight group ($t(51)=-2.16$ $p<.05$, $d=-0.59$).

Between group comparisons

At the fast pace, participants with normal and overweight BMI scores revealed group differences (Tables 3A-C). The overweight BMI group had slower cadences ($t(52)=2.03$

	Normal BMI	Overweight BMI
Cadence (steps/min)	102.48 (2.42)	102.24 (2.00)
Step length (cm)	67.65 (7.33)	67.76 (5.96)
Swing time (msec)	436.04 (10.84)	431.17 (12.26)
Single support time (msec)	436.09 (11.33)	431.39 (12.07)
Double support time (msec)	300.82 (28.99)	314.05 (31.25)
Step time (msec)	586.68 (13.33)	587.74 (11.55)
Stance time (msec)	734.72 (26.88)	743.43 (23.84)
Velocity (m/sec)	1.16 (0.13)	1.16 (0.11)

Table 3A. Means and standard deviations at the normal pace.

	Normal BMI	Overweight BMI
Cadence (steps/min)	81.20 (5.40)	79.98 (2.50)
Step length (cm)	64.68 (7.43)	64.93 (6.72)
Swing time (msec)	547.32 (31.89)	547.93 (24.45)
Single support time (msec)	551.76 (20.87)	549.45 (24.87)
Double support time (msec)	411.91 (44.74)	424.28 (54.56)
Step time (msec)	749.44 (41.94)	759.32 (21.25)
Stance time (msec)	960.66 (40.35)	969.24 (42.90)
Velocity (m/sec)	0.88 (0.12)	0.87 (0.10)

Table 3B. Means and standard deviations at the slow pace.

	Normal BMI	Overweight BMI
Cadence (steps/min)	121.75 (2.86)	119.79 (4.29)*
Step length (cm)	68.45 (10.22)	68.05 (7.71)
Swing time (msec)	373.20 (14.89)	371.86 (16.08)
Single support time (msec)	372.83 (14.93)	372.23 (16.56)
Double support time (msec)	241.23 (30.58)	260.24 (48.82)*
Step time (msec)	493.87 (12.50)	502.29 (18.96)
Stance time (msec)	613.67 (23.14)	631.77 (31.59)*
Velocity (m/sec)	1.39 (0.21)	1.36 (0.16)
*NOTE: *=p<.05*		

Table 3C. Means and standard deviations at the fast pace.

$p<.05$, $d=0.55$) and higher double limb support ($t(52)=-2.23$ $p<.05$, $d=-0.48$) and stance times ($t(52)=-2.42$, $p<.05$, $d=-0.66$) than the normal weight group. Groups showed no differences at the normal or at slow paces in cadence, step length, swing time, single and double limb support time, step time, stance time, or velocity (all $ps>0.1$). At the fast pace, the same was true for step length, swing time, single limb support time, step time, and velocity (all $ps>0.1$).

Matching the metronome pace

Tables 3A-C shows average cadences for each group at all metronome paces. Participants in both the overweight and normal weight BMI groups had cadences that did not match the metronome pace (all $ps<0.001$, minimum $d=-1.15$ and maximum $d=1.99$); at the normal and at the slow paces they walked faster than the metronome, and at the fast pace they walked more slowly than the metronome.

Comparisons between metronome and baseline

Participants' walking parameters at each metronome pace, with the exception of cadence, were compared to their walking at the initial baseline condition with repeated measures ANOVAs. See Tables 2A-B for data from the initial baseline condition and Tables 3A-C for walking parameters at each metronome pace. The 2 (BMI group) x 2 (initial baseline vs. metronome pace conditions) RM ANOVAs revealed main effects for condition at each pace (all $ps<0.01$, minimum $d=-6.08$ and maximum $d=3.04$). However, main effects for group were also found for double limb support times at the normal and at the fast paces and for stance times at all paces; participants in the overweight BMI group had increased double limb support times at the normal and fast paces and increased stance times at all paces compared to those in the normal weight group (all $ps<0.05$, minimum $d=-0.56$ and maximum $d=-0.33$). There were no interactions between group and condition (all $ps>0.1$).

Discussion

The purpose of the current study was to examine how weight classification affects a skill important for maintaining safety while moving: the ability to adapt walking to meet a timing constraint (i.e. walking to the pace of an audio metronome). The findings show that in comparison to the normal weight group, the overweight BMI group had longer double limb support and stance times at the fast pace. Both groups walked faster than the metronome paces at the normal and slow paces and slower than the metronome at the fast pace. However, compared to their baseline walking, participants who were overweight had increased double limb support times at the normal and fast paces and increased stance times at all paces.

Findings during the initial baseline condition confirm some differences found in the literature on walking between adults who are overweight and normal weight[6,9-12]. The only parameters that differed in the current study were double limb support and stance times. Given that participants who were overweight already had higher double limb support and stance times compared to normal weight participants at the initial baseline condition, it is worth noting that they increased those two parameters even more when attempting to walk to the metronome pace. This indicates that those who are overweight are capable of modifying their walking; the overweight BMI group may have been trying to increase biomechanical stability to avoid a loss of balance while attempting to meet the metronome pace[20]. For participants who were overweight, stance and double limb support time may have been the most critical parameters to change to maintain biomechanical stability. Research needs to be done to investigate how maintaining stability can be accomplished without sacrificing accuracy in situations that increase safety risks for adults who are overweight.

Interestingly, neither the normal nor overweight BMI groups exactly matched their cadence to the metronome pace during the conditions. Since there were no consequences for missing the metronome pace, it could explain participants' lack of precision. Previous work has shown improved motor performance when participants receive feedback via knowledge of how they performed[38]. Without the knowledge that they did not meet the pace, participants did not have an opportunity to correct their performance. In addition, simultaneously maintaining speed and accuracy during motor tasks is challenging without co-contracting muscles around the joint involved in the movement[39]. Individuals who are overweight have musculoskeletal and biomechanical differences that affect walking[6,10-12,19] including when they walk at different speeds[20,32,33] which may have influenced their ability to achieve accuracy using biomechanical strategies while trying to meet a timing constraint.

Between-group comparisons revealed differences in cadence, double limb support time, and stance time at the fast pace. Differences may have only been found at the fast pace for several reasons. First, meeting a timing constraint by increasing cadence at a fast pace might be more challenging for those who are overweight than matching a normal or slow cadence. Walking quickly leaves little time to recover from a possible loss of balance. Therefore, participants who were overweight may have sacrificed precision for biomechanical stability. Accuracy when trying to meet a timing constraint can be critical in attempting to time steps appropriately to recover balance and prevent falling[35]. Although previous research shows that participants who are overweight demonstrate signs of safety risks when attempting to match both fast and slow cadences[27], the current study has a larger sample and may therefore be more representative of how BMI affects meeting a timing constraint. Second, there may have been no differences at the normal and slow paces because the influence of BMI may be more extreme for individuals who are obese versus overweight. Research examining gait differences at multiple walking speeds reports differences between normal weight and obese participants[20,32,33]. Group differences between participants who are normal and overweight may be subtler than comparisons between participants who are normal and obese. The differential effects of overweight versus obese BMI scores on adaptation are not well understood. These findings reflect a need to examine how much of an increase in BMI leads to differences in adaptation.

Study limitations

Several limitations to the current study include: 1) using BMI as the main measure of determining weight classification and 2) testing overweight rather than obese participants. First, BMI was used to classify participant groups because it has been used for the same purposes in previous studies. Body composition (e.g., body fat percentage) can provide more precise information about weight status. However, this requires sophisticated equipment, which was not available at the data collection site. Second, differences in adapting to timing constraints may be greater when comparing normal weight versus obese participants. However, the fact that differences were found between normal weight and overweight participants lends more strength to the idea that even small differences in weight classification relates to the ability to adapt motor actions to meet constraints.

Conclusions

These findings suggest that those who are overweight have the ability to alter their motor actions, but tend to alter their gait in ways that allow them to maintain biomechanical stability when attempting to meet timing constraints. Difficulty matching timing constraints may heighten safety risks for individuals who are overweight[27]. They may benefit from interventions to improve the timing of their steps in order to increase safety. These results have implications for the need to create interventions to minimize those risks for adults who are overweight.

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