Impact of excess body weight on walking at the preferred speed

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The implications of a long-lasting mechanical load on the locomotor activity are poorly understood. The objective of the present studies was to determine an impact of excess body weight on basic spatiotemporal gait measures and to test the hypothesis that leg swing phase may account for a load-related adaptation of the stride characteristics. To this end the basic spatial and temporal stride measures were assessed in 100 obese and 36 lean women (age range between 18 and 67 years) walking with their self-selected pace on a 10-meter long and 1 meter wide instrumented pathway. Among the subjects there were: 44 with class I obesity, 27 with class II obesity, and 29 with class III. Subjects' stance and swing times as well as the stride lengths were recorded by means of contact copper-film electrodes attached to a sole of subject's footwear. The acquired gait measures were used then to compute: a mean velocity of walking, double support times and a mean velocity of a foot during swing phase. Data analysis showed that subjects from every experimental groups walked with a very similar speed (1.08 ± 0.2 m/s) and cadence (106 ± 10 steps/min). Their stance time was not affected by body weight and it remained at the mean level of 746 ± 90 ms for all groups. The temporal stride characteristics and the stance-to-swing ratio were, however, substantially modified in obese individuals due to attenuation of the swing time. As a consequence, the remaining normalized (i.e., expressed as percentage of gait cycle time) phases of stride: the stance and the double support were relatively longer. While the swing time negatively correlated with the body mass index (BMI), the normalized stance and the double support exhibited strong positive correlation ($r=0.46$) with the BMI. The increase of leg swing velocity seems the main and unique adaptation mechanism that is utilized in the preferred walking gait in obese women.

Keywords: preferred gait, stride characteristics, body weight, BMI, obesity

INTRODUCTION

Human walk is a biomechanical process involving a complex interplay between muscular and inertial forces that results in the smooth progression of the body through space while minimizing the expenditure of energy (Wearing et al. 2006). The main determinant of walking gait – optimization of energy consumption – is responsible for fine tuning of gait characteristics (Saibene 1990, Bertram 2005). However, in the control of locomotory movements there is a flexibility margin left that allows for adaptation of internally generated optimal neuro-muscular patterns to some mechanical constrains such as support surface conditions, body weight or external mechanical load.

Several studies have been focused on gait adaptation to the external load in such biomechanical conditions as carrying an additional weight (Griffin et al. 2003, LaFlandra et al. 2003, Abe et al. 2004, Bastien et al. 2005). These studies also documented changes in the basic spatiotemporal stride measures due to instant overload of the motor system. For example, LaFlandra and coworkers (2003) showed that the backpack containing load of 40% of body weight significantly affected treadmill locomotion in young healthy subjects expressed as the decrease of stride length with concomitant increase of stride

frequency. The results of these studies cannot be, however, directly transferred to a persistent mechanical load that occurs in obesity. In the latter case, the effects of the long-lasting mechanical load are usually confounded by different adaptive and compensatory strategies.

The implications of the excess body weight on the locomotor activity are poorly understood (Wearing et al. 2006). To date, the limited number of published studies focusing on the obese have encompassed the spatiotemporal gait characteristics (Spyropoulos et al. 1991), the influence of obesity on muscular strength and power (Hulens et al. 2003, Sartorio et al. 2004). Several recent studies aimed on the impact of the excessive body weight on gait energetic in obese adults (Griffin et al. 2003, Hoffman et al. 2004, Browning and Kram 2005, Browning et al. 2009). Relative to the extensive literature now available on many aspects of the obese condition there is a dearth of information pertaining to the functional gait limitations imposed by the body weight. In particular, to date there have been no detailed comparison of the spatiotemporal stride characteristics in subjects with different class of obesity. Thus, the general purpose of the present investigations was to better understand the impact of body weight on the basic spatial and temporal gait measures in healthy lean and obese women walking at their self-selected pace. We hypothesized that the female-type obesity with relatively larger accumulation of a fat tissue in the lower limbs, might result in substantial changes in spatiotemporal stride characteristics mainly due to altered swing phase timing.

METHODS

The research was accepted by the Senate Ethics Committee of the Jerzy Kukuczka Academy of Physical Education. A group of 136 subjects took part in the experiment. All the participants volunteered for a gait study. Before testing, the purpose of the study was explained to the subjects, and informed consent that outlined the subjects' rights was obtained.

The control group (C) consisted of 36 age-matched lean women (BMI = 21.7 ± 1.6 kg/m²). The mean age of the control group was 36.2 ± 10.3 years. Obese participants were patients of the Outpatient Obesity Treatment Clinic at the Silesian Medical University in Katowice. The obese group consisted of 100 subjects in the age range of 18–67 years (mean age: 37.4 ± 11.9 years) with a mean BMI of 37.2 ± 5.2 kg/m². The patients participating in the experiment were diagnosed with obesity of three classes according to WHO criteria (WHO 2000). Among the subjects there were: 44 with class I obesity (group OG I), 27 with class II obesity (group OG II), and 29 with class III (group OG III). The Body Mass Index (BMI – the ratio of individual's body mass in kilograms to her height in meters squared) was calculated for each

Table I

Group characteristics (mean $\pm$ SD, the ranges shown below in parenthesis) of obese and normal weight subjects

Group	n	Age [years]	Body mass* [kg]	Body height [cm]	BMI* [kg/m²]	Waist* [cm]
Control	36	36.2 ± 10.3 (21 − 52)	60.5 ± 7.0	166.3 ± 6.5	21.8 ± 1.7	73.7 ± 4.8
OG I	44	34.7 ± 12.7 (18 − 66)	88.3 ± 6.7	164.3 ± 5.9	32.4 ± 1.6	98.3 ± 5.9
OG II	27	37.5 ± 11.7 (25 − 50)	100.5 ± 8.49	163.7 ± 5.5	37.4 ± 1.3	108.5 ± 6.1
OG III	29	39.5 ± 10.9 (23 − 53)	115.4 ± 9.33	162.3 ± 6.3	43.8 ± 3.1	116.8 ± 8.5

* Significantly different between groups ($P<0.001$)

Table II

Basic temporal and spatial measures of the gait cycle in control (C) and obese (OGI-OGIII) women walking at the preferred speed

Gait parameter	Control	OG I	OG II	OG III	*P*-level
Mean velocity [m/s]	1.08 ± 0.2	1.12 ± 0.2	1.08 ± 0.2	1.03 ± 0.15	NS
Stride length [m]	1.24 ± 0.14	1.24 ± 0.15	1.19 ± 0.15	1.17 ± 0.09	NS
Stride duration [ms]	1165 ± 113	1119 ± 119	1122 ± 111	1154 ± 105	NS
Swing phase [ms]	417 ± 31	390 ± 35	376 ± 28	380 ± 21	$F_{3,132}=12.2$; $P \leq 0.00001$
Stance phase [ms]	748 ± 87	729 ± 90	745 ± 88	772 ± 93	NS
Double support [ms]	166 ± 33	170 ± 34	186 ± 34	196 ± 43	$F_{3,132}=5.1$; $P \leq 0.002$
Stance-to-Swing Ratio	1.79 ± 0.13	1.87 ± 0.15	1.99 ± 0.14	2.03 ± 0.22	$F_{3,132}=15.1$; $P \leq 0.000001$

subject. Group anthropometric characteristics are listed in Table I.

The patients underwent a detailed clinical evaluation. The subjects had no neurological disorders, balance-related pathological conditions or walking impairments, which was determined by a screening evaluation performed by licensed physical therapist in order to ensure that subjects were in good health and had sufficient mobility and strength for gait. Subjects demonstrated sufficient trunk mobility in all planes and complained of no functional limitations in trunk movements. Participants demonstrated the mean lower

Table III

Stance-to-Swing ratio. Results of the *post hoc* analysis (Least Significant Difference)

Group	OGI	OGII	OGIII
Control	0.04	0.000005	0.000001
OGI	–	0.003	0.00004
OGII		–	NS

extremity range of motion needed for normal gait at the hip, knee and ankle joints as reported by Murray (1967). All subjects exhibited good to normal muscle strength throughout both lower extremities based on standard manual muscle testing (Daniels and Worthingham 1980). Lower extremity length (the distance from trochanter major to lateral malleolus) were measured and all subjects were screened for leg-length discrepancy (<0.5 cm).

Our method of spatiotemporal gait diagrams has been described in detail and can be found elsewhere (Afelt et al. 1983, Błaszczyk and Dobrzecka 1989, Plewa et al. 2007). Briefly, spatiotemporal parameters of stride were assessed on an instrumented pathway. The gait-mat was built of 10 m × 1 m conductive wire-mesh fixed to the floor. The ends of the mat were connected to a low power dc voltage adaptor. A linear voltage distribution (10 mV/m) was obtained along the mat, changing it into a linear electronic ruler. The method allows to measure the temporal gait parameters with accuracy of ± 2 ms, whereas the spatial ones i.e., step and stride lengths can be assessed with an error less than 1%.

During the experiment subjects walked back and forth (ten times) at their comfortable pace. Limb

contact signals were recorded by means of copper foil electrodes attached to soles of subjects' shoes. Contacts of the electrodes with the surface of the mat produced electrical signals which parameters were determined by both the position of the contact (amplitude of the stance signal) and the timing of contact (duration of the stance signal). The amplified signals were transmitted to a computer and digitized there with a sampling frequency of 1kHz (Axotape v.2.0, Axon Instrument Inc. USA). Up to four steps during gait initiation and termination were excluded from the analysis and only spatiotemporal measures of steady-state locomotion were taken into account.

Example of a typical spatiotemporal gait diagram assessed during walking is shown in Figure 1. The diagram consists of 2 sequences of rectangular pulses (numbered 1 to 7) with the increasing amplitude. The width of each pulse is uniquely determined by a stance duration (e.g., ST_2 segment in Fig. 1), whereas its amplitude is proportional to the foot's linear position on the path – the distance from the start line of the mat to the point of current limb contact. The interval between the two successive pulses corresponds to a swing time (e.g., SW_3 segment in Fig. 1). The difference between amplitude of the successive stance signals for particular limb determines the stride length e.g., the amplitude of the sixth left leg stride ($LSTR_6$)

in our diagram. The sequences of limb contact signals form a spatiotemporal gait diagram that allows for on-line computation of the following gait parameters (instant and means): walking velocity, stance and swing times, gait cycle (stride cycle), double-support phase durations, cadence, stride length and limb swing velocity (V_{sw}). In steady-state walking, the V_{sw} represents a mean velocity of a foot during swing phase. This parameter was computed in the following way:

$$V_{sw} = \frac{L_{str}}{T_{sw}} - V_m \tag{1.1}$$

since:

$$V_m = \frac{L_{str}}{T_{str}} \quad \text{and} \quad T_{str} = T_{st} + T_{sw} \tag{1.2}$$

therefore:

$$V_{sw} = V_m \frac{T_{st}}{T_{sw}} \tag{1.3}$$

where: L_{str} mean stride length, T_{sw} mean swing time, T_{st} mean stance time, T_{str} mean stride period, and V_m mean velocity of walking

The actual values of the temporal stride indices measured by the system were also normalized i.e., expressed as percentage of a stride time.

All statistical analyses were performed using Statistica v. 6.0 software (Statsoft USA) Each variable was averaged over the ten trials for each subject and these mean values were entered into the statistical tests. The analyses included the calculation of means and standard deviations of the gait parameters for obese and control groups. One-way analysis of variance (ANCOVA with obesity class as a grouping variable and subject's age as a covariant) followed by a *post-hoc* LSD tests were performed to assess differences in spatiotemporal gait parameters between obese groups and the control. Correlation analyses between the gait measures and subject age, body mass, body height, BMI scores as well as lower limb length were performed with the Pearson's test, and with the Spearman Rank Order test for the normalized measures. A *P* level of less than 0.05 was accepted for statistical significance.
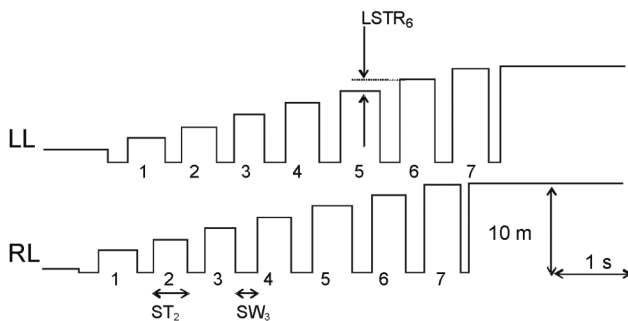

Fig. 1. Typical spatiotemporal gait diagram of the human walking gait (redrawn from the original). It consists from two sequences (for the left LL and right RL leg, respectively) of the square pulses (numbered 1–7) with increasing amplitude. Width of each pulse determines stance phase duration (e.g., ST_2) whereas the break between two successive pulses is equal to the swing time (e.g., SW_3). A difference in the amplitude of two consecutive pulses is proportional to the stride length (e.g., the sixth stride length in the left leg was equal to $LSTR_6$).

RESULTS

Of quantitative interest in the data were effects of the excess body weight in female adults on the spatiotemporal stride characteristics. As designed, body weight and the BMI values differed between groups (Table I). In all subjects stride spatiotemporal measures did not show limb effect (left vs. right leg) and consecutive analysis were performed on collapsed data. Descriptive statistics of the analyzed parameters are summarized in Table II. Analysis of variance exhibited insignificant group effect on a walking velocity ($F_{3,131}$=1.03, P<0.38), on a stride time ($F_{3,131}$=1.33, P<0.27), and on a stride length ($F_{3,131}$=1.58, P<0.20). Comparing the stride length within groups we found that its mean magnitude in the OGIII group was about 6 cm shorter to compare with normal weight subjects, but the level of statistical significance (P<0.06) slightly exceeded the accepted level.

Effects of obesity on the temporal stride characteristics

Some specific for the excessive body weight changes in the stride cycle characteristics have been found. Although the actual values of the stance time did not differ between groups (Table II), the statistical analysis revealed significant effect of group ($F_{3,131}$=16.16, P<0.000001) on the normalized stance duration (the stance time expressed as a percentage of the stride period). The mean normalized stance phase was relatively longer in all obese groups to compare with the normal weight subjects (Fig. 2A). The mean value of the normalized stance phase duration in the lean subjects remained at the level of 64.1 ± 1.6 % of a stride and it was slightly shorter (about 1%) to compare with the OGI group (P<0.02), 2.3% (P<0.000001) vs. OGII group, and 3.6% vs. OGIII group. Statistical differences between all obese groups were also significant (Fig. 2A).
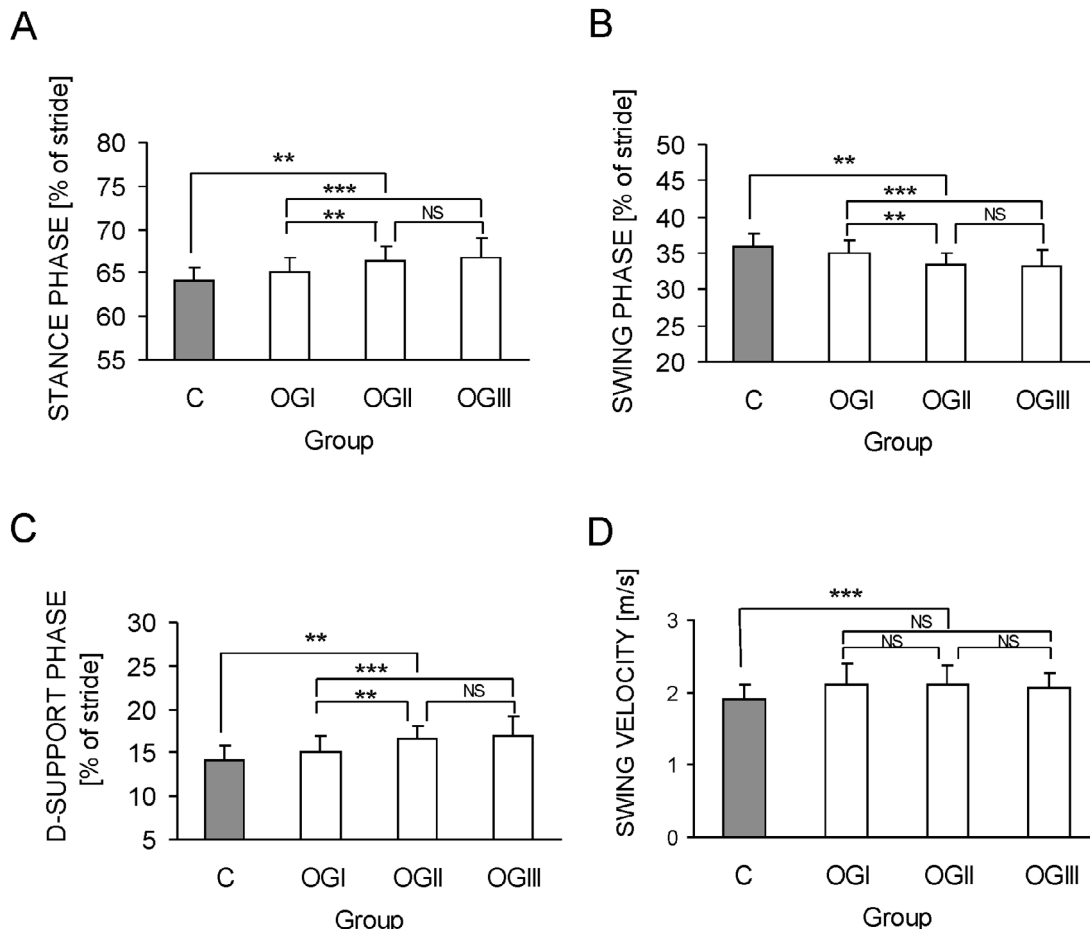

Fig. 2. Gait cycle parameters expressed as a percent of stride cycle and the mean leg swing velocity in control (C) and obese (OGI – OGIII) groups in walking at the preferred speed. ***P<0.001, **P<0.03, (NS) non significant.
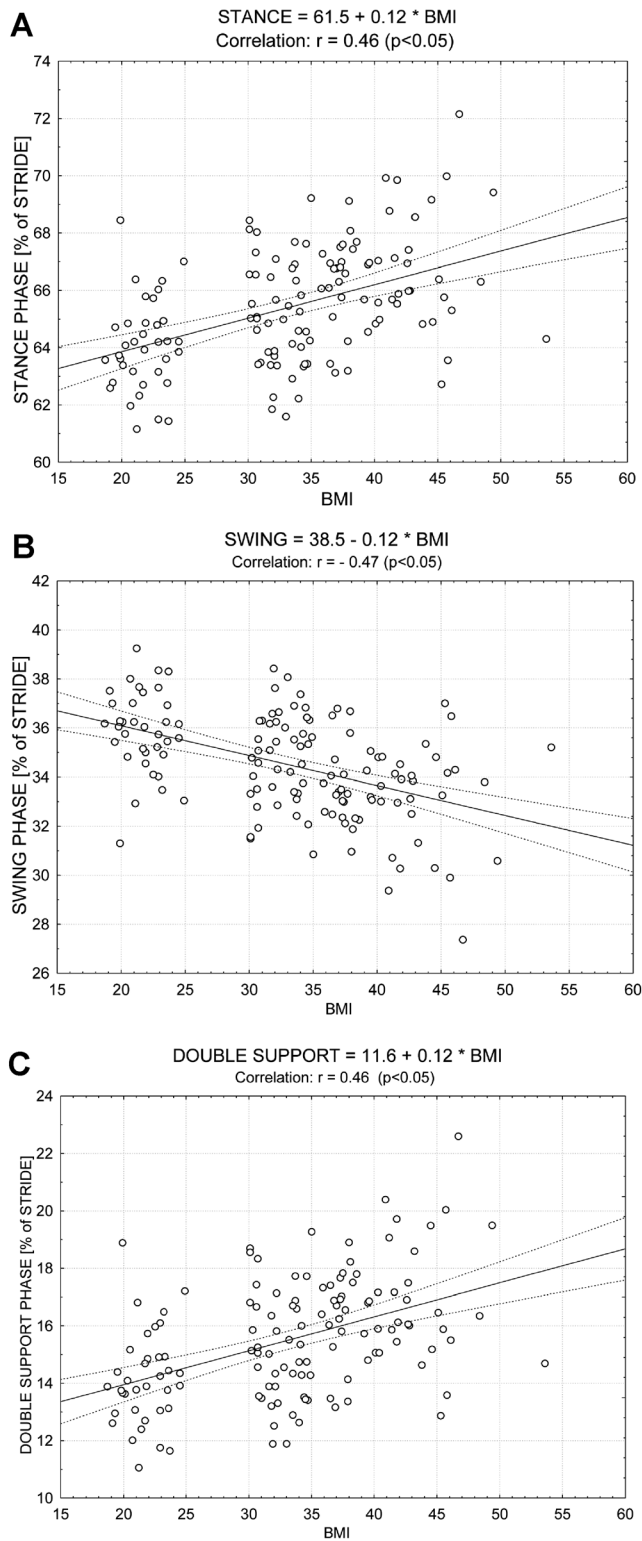
Fig. 3. Changes in the temporal stride measures related to the BMI. Equations of the linear regression and correlation factors are shown above each plot. The 95% confidence interval is marked with a dashed line.
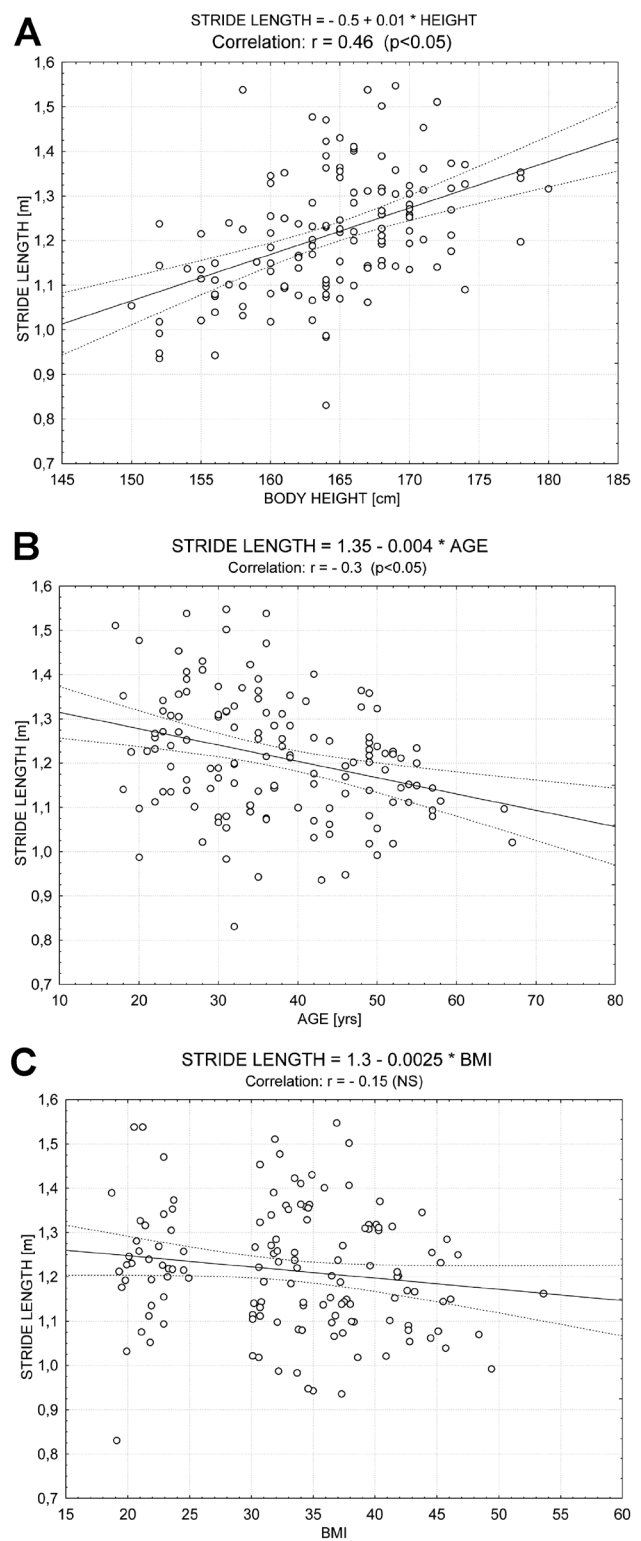
Fig. 4. Impact of body height, subject age and the BMI on stride length. Equations of the linear regression and correlation factors are shown above each plot. The 95% confidence interval is marked with a dashed line.

Walking at the preferred speed in the obese women was characterized by a significantly ($F_{3,131}$=12.01, $P<0.00001$) shorter swing time. The mean values of this parameter were: in OGIII group: 380 ± 39 ms ($P<0.000004$), OGII: 375 ± 37 ms ($P<0.000001$), and OGI: 390 ± 36 ms ($P<0.0002$), to compare with the mean swing time in normal-weight individuals (417 ± 31 ms). Results of the ANCOVA also confirmed significant effect ($F_{3,131}$=16.93; $P<0.000001$) of the group on the normalized swing time i.e., expressed as a percentage of the stride period. Generally, in the obese subjects the mean value of the normalized swing was significantly reduced to compare with the control subjects (Fig. 2B). To compare with the normal-weight women, the swing phase duration was shorter about 6.5% in subjects with the class I obesity ($P<0.0002$), 9.8% in the group OGII ($P<0.000001$) and 8.7% in OGIII ($P<0.000004$).

As the result of aforementioned changes in the stride characteristics in obese women, their mean stance-to-swing ratio increased from normal value of 1.79 (group C) up to 1.87 in OGI, 1.98 in OGII, and to 2.0 in OGIII ($F_{3,132}$=15.1; $P≤0.000001$). Results of the *post-hoc* analysis for the stance-to-swing ratio are summarized in Table III.

The total duration of the double-support phases within gait cycle also differed between groups (Fig. 2C). In the control group, the mean value of this parameter remained at the level 166 ± 33 ms. In obese women we observed an insignificant lengthening of the double-support up to mean value of 170 ± 34 ms in OGI ($P<0.64$) and the significant changes in both OGII (186 ± 34 ms, $P<0.03$), OGIII (196 ± 43 ms, $P<0.0006$). The ANCOVA results showed also significant effect of obesity on the normalized double-support phase (expressed as percent of stride period) to be: ($F_{3,131}$=15.9, $P<0.000001$).

The next parameter to be analyzed was a mean velocity of progression of a foot of the swing leg from the previous to the next support position (V_{sw}). ANCOVA revealed significant effect of excess body weight on the mean velocity of swing. In the obese groups, magnitudes of the mean V_{sw} were significantly greater to compare with the control group ($F_{1,131}$=6.68, $P<0.0004$). *Post-hoc* analysis (LSD test) showed only significant differences between normal weight subjects and the obese groups (Fig. 2D). The obese groups (OGI – OGIII), however, did not differ in the magnitude of the V_{sw}. While the obese subjects walked at the very similar speed, their mean velocity of swing was relatively higher to compare with the normal-weight women (V_{sw} was equal to 2.1 ± 0.27 m/s and 1.9 ± 0.2 for the obese and the control subjects, respectively).

Relationships between spatiotemporal gait parameters and subjects' anthropomorphic measures

The results of the correlation analyses are summarized in Tables IV and V. The basic gait measures i.e., the mean velocity of locomotion was correlated with subject age (r=−0.30, $P<0.001$) but it was not correlated with the body weight nor the BMI. Also the stride length (Table IV and the middle panel of Fig. 5) and the normalized swing phase duration moderately negatively correlated with the age (r=−0.3, $P<0.0001$ for the stride length, and r=−0.37, $P<0.0001$ for the normalized swing). The magnitudes of the normalized stance and the double support phase increased linearly with age (both correlations coefficients were at the level r=0.36, $P<0.0001$). Significant positive correlations were also found between the velocity of walking and the body height (r=0.29, $P<0.001$), and between velocity and the leg length (r=0.21, $P<0.014$).   The normalized swing phase duration negatively correlated with both obesity indices: the BMI (r=−0.46, $P<0.0001$) and the body weight (r=−0.4, $P<0.0001$). Similarly, the normalized stance and the double-support duration were also correlated with body weight (r=0.38, $P<0.05$) and the BMI (r=0.41, $P<0.05$). In Table V we summarized the results of correlation analysis for basic temporal and spatial gait measures as well as for the normalized (expressed in % of a stride cycle). These results showed that the preferred walking velocity correlated in a different way with the swing time (r=−0.45, $P<0.001$) and with the normalized swing (r=0.63, $P<0.01$). Similar diverse effect exhibits correlations for the stance and the swing times (r= 0.61, $P<0.05$) that was in contrast to the negative correlations (r=0.99, $P<0.05$) found between the normalized stance and swing measures. Stance-to-swing ratio positively correlated with the BMI (r=0.45, $P<0.05$), the body weight (r=0.37, $P<0.05$) whereas it negatively correlated with the walking speed (r=−0.63, $P<0.05$). Results of the linear regression analysis are given in Figures 3–5.

Table IV

Correlations between the spatiotemporal gait measures and selected anthropomorphic measures for all subjects ($n=136$, $P \leq 0.05$)

Variable	Walking velocity	Stride time	Stance (%stride)	Swing (%stride)	D. Supp (%stride)	Stride length	Swing velocity
Age	−0.30	0.19	0.25 (0.36)	NS (−0.37)	0.33 (0.36)	−0.30	NS
Weight	NS	NS	NS (0.38)	−0.40 (−0.39)	0.21 (0.38)	NS	0.39
BMI	NS	NS	NS (0.46)	−0.46 (−0.47)	0.26 (0.46)	NS	0.33
Height	0.29	NS	NS (−0.35)	0.26 (0.37)	−0.24 (−0.36)	0.46	0.17

(NS) non significant

Table V

Spearman Rank Order correlations between the spatiotemporal gait measures ($n=136$, $P<0.02$)

Variable	Walking velocity	Stance (%stride)	Swing (%stride)	D.supp (%stride)
Stance (%stride)	0.84 (−0.64)	–	0.61 (−0.99)	0.91 (0.99)
Swing (%stride)	−0.45 (0.63)	0.61 (−0.99)	–	0.27 (0.99)
D.supp (%stride)	−0.82 (−0.63)	0.91 (0.99)	0.27 (0.99)	–
Stride length	0.86	−0.49 (−0.59)	NS (0.60)	−0.56 (−0.59)
Swing velocity	0.80	−0.61 (NS)	−0.69 (NS)	−0.43 (NS)
Stance-to-swing ratio	−0.63	0.65 (0.99)	NS (0.99)	0.89 (0.99)

(NS) non significant

A

STANCE = 63 + 0.07* AGE
Correlation: r = 0.36 (p<0.05)

B

SWING = 37 - 0.07 * AGE
Correlation: r = - 0.37 (p<0.05)

C

DOUBLE SUPPORT = 13 + 0.07 * AGE
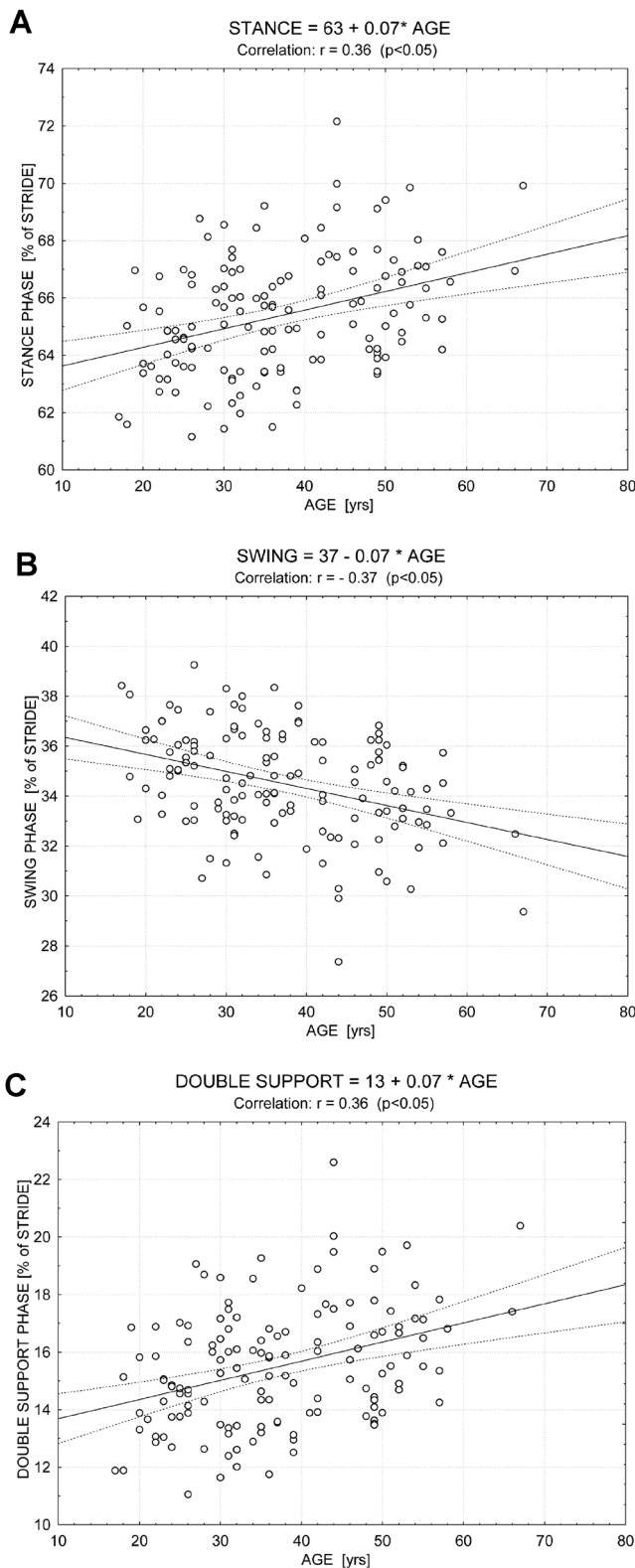Correlation: r = 0.36 (p<0.05)

Fig. 5. Age-related changes in the temporal stride characteristics. Equations of the linear regression and correlation factors are shown above each plot. The 95% confidence interval is marked with a dashed line.

DISCUSSION

A primary objective of this study was to determine effects of the excess body weight on spatiotemporal walking characteristics. Our results showed that a persistent overload of the locomotor system had no discernible effect on the preferred velocity of walking, on the stride cycle and the stride length. The overall temporal structure of the stride cycle has been, however, substantially modified towards a shorter swing time. This resulted in a relative lengthening of normalized stance and double support phases.

The documented here changes in the spatial and temporal stride measures can be explained based upon constrained optimization hypothesis (Bertram and Ruina 2001, Bertram 2005). According to the hypothesis, during walking at the self-selected pace the unique set of basic gait parameters i.e., speed, cadence and stride length is selected to optimize gait energetic cost. Walking at the preferred speed determines the absolute minimum of the energetic cost (Bertram and Ruina 2001). In this multi-dimensional minimization process the nervous system defines the optimal stride characteristics. Since the walking speed is uniquely determined by the stride length and the stride cycle (Afelt et al. 1983, Winter 1987, Błaszczyk and Dobrzecka 1989, see the equation 1.2) the discussion will focus on the impacts of the excess body weight on the both walking velocity determinants.

First quantitative temporal and spatial aspects of gait have been reported for obese men by Spyropoulos and coworkers (1991). In their investigations, the average value of the obese group for speed was 1.09 m/s and for stride length 1.25 m. The mean values of their non-obese individuals were unfortunately taken from the laboratory database; they were surprisingly high: the mean preferred speed in the control group was 1.64 m/s, and the reported stride length ranged 1.67 m. Within the limited literature, the preferred walking speeds have been consistently reported to be slower in obese men (Spyropoulos et al. 1991, Pisciotta et al. 1991), and in obese children (Hills and Parker 1991, McGraw et al. 2000) when compared with normal-weight individuals. Mattsson and coworkers (1997) and Melanson and others (2003) reported the preferred speed of 1.18 m/s for class II obese adults. However, Browning and Kram (2005) found no difference between young class II obese and normal weight females in the preferred speed, and even they showed that young obese females walked faster (1.4 m/s) than

the speed that minimized gross energy cost per distance (1.25 m/s). The preferred velocity of walking in our control group was slightly lower than in the previous studies. What is more striking, it remained at the same level in all obese groups (1.08 m/s). This may suggest that the preferred speed is a main invariant in the gait adaptive strategy.

It has been previously suggested that optimal walking speed for net cost minimization should be around 1.06 m/s (Griffin et al. 2003, Bastien et al. 2005). This optimal value almost perfectly corresponds to walking velocity measured in our studies which were performed on a large sample of female subjects. Some discrepancies in the preferred speed reported in the literature might result from the fact that most of the data were assessed in diverse (usually consisting of subjects of both genders) and relatively sparse experimental groups. Our results of correlation analyses showed that subject anthropometric characteristics (in particular body height and the limb lengths as well as their age) may substantially affect the preferred speed of walking. Other minor discrepancies in the spatiotemporal gait characteristics may be accounted for measurement techniques applied in different studies. In particular, while we applied the high resolution spatiotemporal gait diagram method, Spyropoulos and colleagues (1991) and DeVita and Hortobagyi (2003) used less accurate cine techniques that allowed to record motions of the limb segments at 50 or 60 frames per second. Thus their temporal measurements (swing and stance time) was limited to ± 20 or ± 15 ms resolution, respectively. The accuracy of their stride length assessment has not been disclosed. The experiments on gait energetic cost in obese were traditionally performed on a treadmill (Browning and Kram 2005, Brawning et al. 2006), which may also affect gait pattern and probably the preferred speed of walking.

One of the most intriguing finding which emerged from the present study was surprisingly selective impact of excessive body weight on stride measures. The swing and the double support times were mainly affected by the excessive body weight. This finding is in contrast to results of earlier studies. Majority of authors, while studying different aspect of walking in obese subjects reported gait alternations to compare with normal-weight subjects: the reduced stride length (Pisciotta et al. 1991, Spyropoulos et al. 1991, Messier et al 1996, Hulens et al. 2003), the longer cycle duration (Spyropoulos et al. 1991, Hills and Parker 1991) and the

lower cadence (Spyropoulos et al. 1991, Messier et al. 1996, McGraw et al. 2000, Hulens et al. 2003). The authors pointed out the lengthening of the stance time as a key mechanism for the compensatory adjustment of stride characteristics. Recently, DeVita and Hortobagyi (2003) investigated kinematics and kinetics of 21 obese adults walking at both the preferred and the standard (1.5 m/s) speeds relative to 18 non-obese adults walking at a standard speed. Consistently with our results, their obese participants, while walking with the same speed, exhibited stride characteristics similar to those used by normal-weight subjects. In particular, the step length and the step frequency were not significantly different between groups.

Mean values for the stride length reported here (1.22 m) were at the same level in all groups and they were virtually independent on subject's body weight. Only some minor though statistically insignificant shortening of the stride length (5 and 6 cm for the OGII and OGIII group, respectively) has been documented. The results of correlation analysis showed that the stride length is determined mainly by the body height ($r=0.46$) and consequently by the limb length ($r=0.39$). Additionally, we observed a pronounced effect of subject's age on all the basic temporal and spatial measures of the gait cycle. The age significantly correlated with the stride length and with the stride cycle and the stance time. In obesity, excess of body fat is accumulated over the years, accompanied by natural ageing of the nervous system. The ageing process is associated with neurons degeneration in the most crucial for locomotor control structures: motoneurons of the spinal cord, cerebellum and substantia nigra (Turlejski and Djavadian 2002). These age-related neurodegeneration effects may be responsible for some discrepancies in the spatiotemporal gait characteristics reported here and in the previous studies for obese adults (Sartorio et al. 2004).

Basic spatial and temporal measures of gait cycle offer fundamental information regarding the overall gait control. Unfortunately, these measures are very sensitive to walking speed (Winter 1987). As we have shown here the stance, swing and double support durations were negatively correlated with the walking speed at the level of −0.83 for stance, −0.79 for the double support and −0.47 for the swing time. Thus the effect of walking speed additionally complicates the analyses of the data (e.g., Spyropoulos et al. 1991). Transformation of the basic temporal measures to a percentage of gait cycle is a commonly accepted

method for the data normalization (Winter 1987). The main advantage of the normalization is elimination of walking-speed effect on stride measures variation in addition to a reduction of inter-subject gait value variation due to subject-specific anthropomorphy (e.g., subject height and weight). We should keep in mind that the raw spatiotemporal gait measures and the normalized ones provide us with very different information on the control mechanisms of locomotion (see Table V). Results of analyses performed on the normalized stride measures might be sometimes misleading.

Since our subjects preferred walking at the very same speed we were capable of comparing directly the load-related effects on both the actual and the normalized gait characteristics. In addition to the swing and the double support times that were directly affected by the excess body weight, most of the normalized stride measures exhibited a significant dependence on the body weight. We report, however, lower magnitudes of changes in the normalized stride characteristics to compare with the results of DeVita and Hortobagyi (2003). These authors showed 5% shorter normalized swing, whereas the normalized stance was 3% longer in obese compared to lean participants. Collectively, all the changes were interpreted as representing an underlying instability in the obese, with a shorter swing, longer stance, and period of double support thought to assist the maintenance of dynamic balance (Spyropoulos et al. 1991, Olney and Richards 1996, Hills et al. 2002). According to Olney and Richards (1996) extended periods of double support during locomotion are also detrimental for energy conservation. Although in our research we observed the same tendency of changes, the documented here increase of the normalized stance and the double support periods ranged only: 0.9% for the first class obesity (group OGI), 2.3% for the OGII subjects, and 2.8% for the OGIII group. Decrease of the normalized swing remained at the same level of 1%, 2.3%, and 2.8% for the OGI, OGII, and OGIII groups, respectively. Such slight changes are probably ineffective to improve postural stability and they certainly are insufficient to compensate for the increased mechanical load. The most striking result of this study was luck of an impact of body weight on the duration of stance. As a consequence, the documented here shortening of the swing time while the stride period remained unchanged resulted in a relative lengthening of both normalized

phases of stride: the stance and the double support. These effects support the notion that in obese individuals the attenuation of the swing time might improve stability of walking at preferred speed.

An understanding of the effects of excessive body weight on swing phase mechanics is critical for the main tasks of locomotor control: progression, maintaining dynamic stability and shock absorbing (Winter 1987). The principal swing phase task is the progression of the foot of the swing leg from the previous to the next support position, providing the basis for the forward progression of the body (Mills and Barrett 2001). The leg swing movement is performed with an optimal speed that also depends on limb inertia (Doke et al. 2005). Female obesity (gynoid adiposity) has distinct characteristics; the increased body weight is combined with relatively larger accumulation of a fat tissue in the lower limbs, especially in the hips and thighs (LaFortuna et al. 2005). Thus, greater mechanical work may be required to swing the relatively heavier legs (Doke et al. 2005, Royer and Martin 2005, Browning et al. 2006). Doke and coworkers (2005) analyzed work and energetic cost related to leg swing in healthy young adults subjects. They estimated that moving legs back and forth at a typical stride frequency might consume as much as one-third of the net energy needed for walking at optimal speed. Experiments on walking with additional weight confirmed also that the gait metabolic expenditure is much grater when the weight is placed on the thighs compared to waist load (Royer and Martin 2005). Documented in this study faster leg swing in obese groups may be a consequence of both, the increased stance-to-swing ratio (equation 1.3) and a wider step width (Spyropoulos et al. 1991).

CONCLUSIONS

The study documents adaptive changes to the spatiotemporal gait characteristics due to a persistent overload of the locomotor system in obese women. We showed that the increased body weight imposed new biomechanical constrains that resulted in the modifications to the spatiotemporal stride characteristics without noticeable impact on the preferred walking speed and on the stride length. The documented here shortening of the swing time while the stride length remained unaltered resulted in a significant increase of both limb swing velocity and the stance-to-swing ratio.

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