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Running head: Stability and trunk coordination in Nordic walking

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Abstract

Mechanical work generation and muscular activation from upper limbs are increased during Nordic walking. However, no investigation has compared the margins of stability and scapular-pelvis coordination between walking with and without poles. Our aim here was to compare margins of stability, activation of a hip stabilizer muscle and scapular-pelvis coordination (mean and variability of continuous relative phase) between walking and two different pole walking techniques (observational design). Eleven Nordic walking instructors were asked to walk at 5.5 $km \cdot h^{-1}$ on a flat treadmill while 1) walking, 2) Nordic walking and 3) elbow technique, using poles with just elbow flexion-extension motion allowed and constrained shoulder motion. The 3D movements of limbs and poles were measured by an optoelectronic motion capture system and the activation of *gluteus medius* was measured through surface electromyography. Both techniques using poles show larger mediolateral margins of stability and similar anterior-posterior margins of stability in comparison with walking ($p<0.001$). The larger mediolateral margin of stability using poles (conditions 2 and 3) is accompanied by a higher trunk coordination stability (continuous relative phase variability) compared to walking. Although the Nordic walking (condition 2) technique results in a similar amplitude of scapular and pelvis transverse rotation, the general pattern of scapular-pelvis coordination was changed (delayed) temporally in 20% of the gait cycle in relation to other conditions (1 and 3). In conclusion, Nordic walking provides enhanced mediolateral support and trunk coordinative stability than walking, resulting in a safe exercise modality.

***Keywords*:** Locomotion, Pole walking, Dynamical stability, Postural balance, EMG, Continuous relative phase.

1. Introduction

Walking with poles is an attractive mode of physical activity for fitness (INWA, 2015). The main reasons for the increasing popularity are physiological and biomechanical alterations of using poles in comparison with walking that result in increased energy expenditure despite reduced perceived exertion (Figard-Fabre et al., 2010). Greater expenditure have been attributed to an increased internal mechanical work from upper limbs and to higher activation of trunk and upper-limb muscles elicited by the poling actions (Pellegrini et al., 2017, 2015; Zoffoli et al., 2017, 2016).

This higher activation during NW in comparison to walking is accompanied by alterations in muscle synergies from upper limbs (Boccia et al., 2018). Despite the significant coordinative role of scapular and pelvic girdle motion on gait (Van Emmerik et al., 2005), the determination of girdle movement patterns when using poles have received little attention. Indeed, even in coordination studies, the continuous relative phase (a measure, which describes the phase space relation between two joints throughout the movement) and the variability of continuous relative phase (stability of the system, or its resiliency to perturbation) of scapular and pelvic girdles underlying the usage of poles is still unclear (Boccia et al., 2018; Zoffoli et al., 2017).

Investigations on the dynamics of human walking showed that bipedal walking is passively stable on sagittal plane, requiring an active feedback control on mediolateral motion, usually done by adjustments in foot placement (Donelan et al., 2004; Kuo, 1999) together with hip abductor muscles as *gluteus medius* (Boccia et al., 2018). The gait is mediolaterally stable when the mediolateral velocity-adjusted position of the center of mass is maintained inside the mediolateral edge of the base of support thus resulting in positive mediolateral margins of stability (Hak et al., 2013; Hof et al., 2005). Probably, the use of poles could contribute to these control tasks, by maintaining the stability through increasing base of support, resulting in larger mediolateral margins of stability (Hof et al., 2005).

Finally, another factor that has the potential to affect the dynamic stability of walking is that most of the differences in muscle activation and movement patterns occur in the trunk and upper limb regions (Bombieri et al., 2017; Gomeñuka et al., 2020; Nardello et al., 2017), therefore, the trunk coordinative stability possibly mediates the alterations in dynamic stability by using poles. The *gluteus medius* also acts controlling mediolateral movement of the trunk (Boccia et al., 2018), thus, might be another candidate to understand the alterations related to mediolateral stability during NW. Also, changes in the way the poles are used can alter trunk coordination and margins of stability. Recent findings have shown that when using a technique based strictly on elbow movement (with restricted shoulder movement), a lower triceps brachii muscle activation and reduced propulsive polling action with respect to NW were seen, resulting also in shorter steps (Pellegrini et al., 2018). Probably these alterations may alter the trunk coordination and margins of stability.

Thus, the purpose of this observational study was to investigate whether the usage of the poles, and techniques adopted using poles, affect the margins of stability, electromyographical activity of *gluteus medius*, and trunk and joint coordination during walking. To address these aims, we compared walking with two different pole walking techniques, the one considered the correct technique (NW, using the poles actively and dynamically and controlling the poles by hand gripping with a grasp/release pattern, maintain range of arm motion similar to walking, maintaining a backward pole position on the propulsion phase) and a second technique predominantly based on elbows flexion/extension (elbow technique). This condition has been included as one of the most common deviation from the suggested technique seen while people are walking with the poles (Pellegrini et al., 2018). We hypothesized that the dynamical stability will increase using poles particularly on control of mediolateral stability, independently of the technique used, and the greater stability should be accompanied by a reduced muscle activation of the *gluteus medius*. Our secondary hypothesis is that the correct technique of NW will generate improvements in trunk coordinative stability demonstrated by the greater variability in continuous relative phase angle of scapular and pelvis girdles.

2. Methods

2.1. Participants

This study was approved by the local Ethics Committee and performed in accordance with the Helsinki Declaration. A written informed consent was obtained from all participants and STROBE guidelines were used to ensure the reporting of this observational study (cross-sectional type, Supplementary material 1).

The sample size of eleven subjects was needed to detect a difference using a power as 1-beta error probability: 85 %; effect size: .85; error assumed as alpha: .05 based on Hak's study for the margins of stability (http://hedwig.mgh.harvard.edu/sample_size/js/js_crossover_quant.html, Supplementary material 2) (Hak et al., 2013). The eligibility criteria were evaluated throughout personal interviews: *i)* to be licensed as instructors by INWA (International Nordic Walking Association), *ii)* no musculoskeletal problems (muscle, tendon, joint or bone pain or injury), and *iii)* regular NW practise within the last year (without stop longer than 2 weeks). The eleven subjects (5 females and 6 males) recruited were between 20 and 55 years old with body mass index in the normal range. The sample characterization is presented in Table 1.

2.2. Data collection

The individuals were asked to walk on a motorized treadmill (belt surface 3.5 m long and 2.5 m wide; RL3500E, Rodby, Vänge, Sweden) for 5 minutes, at 5.5 km·h^{-1} and 0% of incline, at three conditions: walking, NW and pole walking with just elbow flexion-extension (elbow technique), and the time interval between tests was 10 minutes. The speed of 5.5 km was chosen because it is commonly used by NW users (Church et al., 2002). In the NW condition, the individuals performed the diagonal technique recommended by INWA. Briefly, INWA indicates that propulsion done by arms through the pole needs to be performed with the elbow completely or quasi-completely extended and the extensor shoulder muscles are contributors to poling phase (Pellegrini et al., 2017). In the third condition, elbow technique, the individuals were asked to walk with the poles by performing the poling action through an elbow flexion-extension pattern while minimizing shoulder contribution to the upper-limb swing. Tests were executed in a random order on a single visit. Individuals utilized NW poles (Exel, Nordic Walker, Espoo, Finland) furnished with special carbide tips to ensure proper grip with the treadmill surface. The pole length was defined by multiplying the instructor's height by .68, with a tolerance of .025 m (INWA, 2015).

The 3D movement of body segments was registered at a sample frequency of 100 Hz using a 6-camera infrared Motion Capture system (MCU240, ProReflex; Qualisys, Gothenburg, Sweden). Semi-spherical reflective markers were placed on glenohumeral joints, humeral lateral condyles, ulnar styloids, greater trochanters, femoral lateral condyles, lateral malleolus and over the shoes, in proximity of the metatarsal head II. Two further markers were placed on each pole in the two tertiles of the pole's length.

Track Manager software (Qualisys, Gothenburg, Sweden) was used for calibration and data acquisition procedures.

EMG signals were recorded at a sample frequency of 2048 Hz using a multichannel amplifier (EMG-USB2, OT Bioelettronica, Turin, Italy) with a recording bandwidth 10-500 Hz. The procedures to evaluate the muscular activation of the *gluteus medius* in the right side were started with the skin preparation and electrode placement and was performed by the same experimenter for all participants. Bipolar Ag/AgCl surface electrodes with a 15 mm total diameter (Spes Medica, Battipaglia, Italy) were used, respecting an inter-electrode distance of 2 cm (De Luca, 1997). The reference electrode was placed at the tuberosity of the right tibia. An initial assessment was performed to check for cross talk and cable-induced noise and, when needed, electrodes and cables were repositioned. The cables and electrodes were secured and fixed on the body of the participants with an extensible dressing (Fixomull®, Beiersdorf, Hamburg, Germany) to avoid movement artefacts.

After electrodes placement, the subjects were instructed to perform a warm-up by walking for 5 min on the treadmill. Activation correspondent to maximal isometric voluntary contraction was then obtained from *gluteus medius* by encouraging the subjects to exert the maximum force by leg abduction against immovable resistance provided by a rope hanged to a fixed bar, with straight hip and knee lying on the left side. Three measurements of 5 s maximal voluntary isometric contraction (with intervals of 1 min in between) were obtained and we used the highest value to normalize the EMG activation in each walking condition. During the walking exercises, kinematics and EMG data were registered for a duration of 30 seconds in the last minute of the 5-min tests.

2.3. Data analysis

The procedures to processing stride length, EMG, range of motion, trunk and interjoint coordination, and margins of stability parameters are presented in detail in Supplementary material 3.

A 3D kinematic model already established in our laboratory (Pellegrini et al., 2017) was used to calculate the stride length, range of joint motion, dynamical stability and motor coordination. The stride length was calculated as the product of average speed and average time of strides. For EMG signal of *gluteus medius*, the root mean square values were calculated after filtering (Butterworth, 4th order, 20-400Hz), and normalized to maximal voluntary isometric contraction. The range of motion was considered as the total excursion of joints and girdles analyzed. All biomechanical and coordination parameters were calculated on the body's right side.

The continuous relative phase of the following pairs of girdles and joints were calculated: scapular and pelvis or intergirdles, elbow-shoulder, hip-knee, knee-ankle. The continuous relative phase is the difference in phase angles of the two original signals representing dynamic coordination of these variables, the phase space relation between two joints or girdles dynamically (Lamb and Stöckl, 2014; Van Emmerik et al., 2005). The mean value (from 10 stride cycles) of the continuous relative phase during each phase (all, 0-20%, 20-50%, 50-80% and 80-100% of the contact phase) was calculated to investigate the coordination pattern in a specific phase of the gait cycle. The variability of the continuous relative phase of the same pairs of girdles and joints (scapular-pelvis or intergirdles, elbow-shoulder, hip-knee, knee-ankle) was calculated as the mean value of the standard-deviation (from 10 stride cycles) of the continuous relative phase. This parameter represents the stability of the local motor system, or its adaptative capacity to perturbations (Lamb and Stöckl, 2014; Van

Emmerik et al., 2005). The degree of uncertainty (systematic and random error of measures) and feasibility applying this technique (based on Hilbert transform) were recently tested (Mehdizadeh and Glazier, 2018). Similarly to continuous relative phase, the discrete phase difference is the temporal difference on events relative to changes of direction/phase between girdles (scapular-pelvis) and joints (elbow-shoulder, hip-knee, knee-ankle) as a fraction of stride. Values around 180 degrees indicating "out-of-phase" coordination (opposition), and values close to 0 degree demonstrate "in-phase" coordination (*en bloc*). The dynamical stability was calculated through the determination of anterior-posterior and mediolateral margins of stability. The anterior-posterior and mediolateral margins of stability were calculated as the difference between the anterior-posterior and mediolateral boundaries of the base of support versus the position of the extrapolated center of mass (representing the state of the center of mass taking into account both its position and velocity) in the anterior-posterior and mediolateral directions, respectively (Hak et al., 2013; Hof et al., 2005). Besides the determination of margins of stability total considering the largest base of support, we calculated the margins of stability using just the feet as reference even in pole conditions to determine possible body adjustments using poles in the margins of stability. Also, we determined the delta values of *gluteus medius* activity and lateral margins of stability, subtracting these values during NW and elbow technique conditions versus walking condition. These delta values were used to test possible relations between lateral stability and muscular activity using poles.

The dataset with individual data is in Supplementary material 4.

2.4. Statistical Analyses

The parameters described above were averaged over 10 consecutives stride cycles. Generalized linear analysis models (GLMM) and Bonferroni post hoc tests were used to evaluate differences between the walking, NW, and elbow technique conditions. The data analysis was based on the Wald chi-square test (x^2) and it was adjusted as linear or gamma distribution, according to the Akaike's information criterion (Nelder and Wedderburn, 1972). Analyses included stride length, EMG, range of motion, interjoint and intergirdle coordination (continuous relative phase angle, continuous relative phase angle variability and phase difference), and mediolateral and anterior-posterior margins of stability. We tested the correlation between delta-conditions (walking – NW, and walking – elbow technique) using Pearson's correlation tests. The significance level adopted was α=.05 for all tests at SPSS software (Statistical Package for Social Sciences for Mac, version 22.0). The effect sizes (by Hedges's g method) were calculated using values between conditions and were classified as small (between .20 and .49), moderate (between .50 and .79) and large effect (.80 or more). The results were presented as means, standard deviation, and 95% confidence intervals.

3. Results

The stride length, EMG, range of girdle and joint motion, stability, and coordinative variables are shown in Table 2. The post hoc comparisons are in Table 3. Examples of range of joint and girdle motion and continuous relative phase angle for one individual divided by stride and averaged (SD) during NW are in Supplementary material 5 and 6, respectively.

3.1. Neuromuscular and biomechanical parameters

The EMG activation from *gluteus medius* (Figure 1) was similar between all conditions ($x^2(2) = 5.3$, $p = .069$). Stride length was affected by condition (main effect, $x^2(2) = 35.1$, $p = .001$) in which it was largely higher in NW than walking and elbow technique conditions ($p < .001$) and the elbow technique was similar to walking condition ($p = .195$; Table 2 and Figure 1).

*** figure 1 here***

The range of ankle and knee motion remained unaltered between conditions. Conversely, the range of hip motion during NW presented a higher value than walking, respectively 42.6 ± 7.9 degrees versus 36.0 ± 3.0 degrees (main effect, $x^2(2) = 12.5$, $p = .03$; post hoc, $p = .002$). While the range of elbow motion at sagittal plane was unaltered between conditions, the range of shoulder motion for elbow technique was lower than both NW and walking, respectively, 22.1 ± 5.6, 45.7 ± 7.6, and 48.5 ± 1.6 degrees (main effect, $x^2(2) = 98.8$, $p < .001$; post hoc, $p < .001$). The range of scapular girdle motion in the transverse plane was reduced using elbow technique in comparison to other conditions [elbow technique: 4.0 ± 1.5 degrees, NW: 9.0 ± 4.5 degrees; walking: 7.8 ± 3.2 degrees; Hedges' g between NW and elbow technique is -1.4 (large effect, 95.0%CI -2.1, -.8); Hedges' g between walking and elbow technique is -1.5 (large effect, 95.0%CI -2.4, -.4); main effect, $x^2(2) = 25.7$, $p < .001$]. The range of pelvis rotation was similar between conditions (main effect, $x^2(2) = 5.0$, $p = .084$).

3.2. Stability and coordinative parameters

The continuous relative phase angle of scapular and pelvis girdles was altered using the NW (Figure 2) shifting about 20% in comparison to elbow technique and walking. The continuous relative phase angle of elbow and shoulder joints at sagittal plane was higher for NW in comparison to walking (main effect, $x^2(2) = 30.5$, $p = .001$, Figure 2 and

Supplementary material 6). The continuous relative phase angle from lower limbs was similar between NW and elbow technique versus walking (Figure 2 and Supplementary material 6). However, the continuous relative phase variability of scapular and pelvis girdles was steadily higher for NW versus elbow technique during whole stance, and versus free walking at final (80-100%, push-off) stance (Tables 2 and 3). The continuous relative phase variability of scapular and pelvis girdles (Tables 2 and 3) and upper limbs (elbow and shoulder joints, Figure 2 and Supplementary material 6) was similar between walking and elbow technique.

figure 2 here

The phase difference is shown in Figure 3. The phase difference shows consistently a pattern in-phase similar in all conditions for lower and upper limbs. Nevertheless, the phase difference shows a high variability for scapular-pelvis transverse girdles, especially for NW and elbow technique (Table 2 and Figure 3). While the phase difference was out-of-phase in walking, the two techniques of NW show an unclear pattern (Figure 3).

figure 3 here

The margins of stability are shown in Table 2 and Figure 4. The movies showing the base of support from one individual in walking, NW and elbow technique conditions can be seen in Supplementary material Movie 7a, Movie 7b and Movie 7c, respectively. The mediolateral margins of stability were higher in NW and elbow technique than walking (main effect, $x^2(2) = 18.0$, $p < .001$). The body margins of stability disregarding poles in the calculation (analyzing just the body), however, were similar, between condition (main effect, $x^2(2) = 1.9$, $p = .376$). The use of poles did not change significantly the anterior-posterior margins of (main effect, $x^2(2) = 1.6$, $p = .443$).

figure 4 here

The correlation between delta-conditions for *gluteus medius* activation versus mediolateral margins of stability in the pair were at walking – NW, *R*= .52, p = .101, and at walking – elbow technique, *R*= .64, p= .034, indicating that larger increments in mediolateral margins of stability were related to higher reductions in muscle activation of *gluteus medius* comparatively between conditions elbow technique versus walking (Figure 5).

figure 5 here

4. Discussion

The present study aimed to investigate whether the use of the poles influences the margins of stability during the locomotion as well as interjoint and intergirdle coordination. The main findings of this study confirmed *i)* our first hypothesis that the dynamical stability is enhanced when using poles, *ii)* with higher margins of stability in the mediolateral direction in NW and elbow technique than in walking; *iii) gluteus medius* muscle activation is moderately reduced and *iv)* trunk coordinative stability is improved when using the poles. In line with our second hypothesis, the continuous relative phase variability between scapular and pelvis girdles was increased using the suggested NW technique in comparison to elbow technique condition.

The general values of margins of stability and scapular-pelvis coordination were quite comparable to findings previously reported for walking (Hof et al., 2005; Lamb and Stöckl, 2014). Also, the EMG values recorded for walking and NW were consistent with previously reported value (Pellegrini et al., 2015).

The results for joint kinematics are in line with previous studies showing that knee and ankle joint flexion-extension results unaltered using poles (Pellegrini et al., 2017). The increased range of hip motion was accompanied with a larger pelvis excursion at transverse plane. Possibly this specific aspect contributes to a longer stride, bouncier technique and, consequently, to a more pendular gait (Pellegrini et al., 2017). One critical mechanical determinant of inverse pendulum model in walking is related to pelvic transverse rotation also considered as one of the major determinants of gait (Cavagna et al., 1976; Saunders et al., 1953). Also, our findings showing a similar range of scapular transverse motion between NW and walking conditions, counter-indicating the views based on common sense that the NW increases the rotation of scapular girdle (Anttila et al., 1999). Further, if the elbow technique is applied, the scapular transverse rotation is reduced significantly in comparison to walking and NW conditions.

4.1. Intergirdle and interjoint coordination

The variability of continuous relative phase represents the stability of the musculoskeletal system to perturbation (Lamb and Stöckl, 2014). The present findings show a greater stability in the trunk coordinative structure (variability of continuous relative phase of scapular and pelvis girdles) using poles. Possibly, these findings together to larger mediolateral margins of stability may justifying the lower ratings of perceived exertion using poles in comparison to walking condition (Figard-Fabre et al., 2010). Indeed, since the effort perception in exercise is influenced by safety and stability (Ishizuka et al., 2011), the discrepancy in metabolic cost and rating of perceived exertion seen using the poles in standardized and outdoor environments (Figard-Fabre et al., 2010; Grainer et al., 2017) may be at least partly explained by the changes in coordination and dynamical stability found in the present study. On the other hand, maintain the body stability is associated with an additional metabolic cost (Ijmker et al., 2013), thus, the higher metabolic cost of NW in comparison to walking may be attributed with the higher stability using poles. Therefore, future study is needed analyzing the dynamical stability, ratings of perceived exertion, and metabolic cost to respond satisfactorily this question.

4.2. Balance: margins of stability and EMG

The larger mediolateral margins of stability found when the poles are used was associated to a decrease in the activity of the *gluteus medius* muscle just using the elbow technique. This is somehow in agreement with a study that has demonstrated a reduction in the activation of *gluteus medius*, *gluteus maximus* and *tensor fascia latae* muscles, with respect to conventional walking when the walkers use the poles vertically (similar to elbow technique), like canes (Homma et al., 2016). The role of *gluteus medius* in walking is to stabilize the pelvis to prevent an exaggerated pelvic tilt (Semciw et al., 2013). Also, the decreased activity of this muscle, due to elbow technique, leads then to propose that when using this more vertical strategy, the poles play an important role in supporting the pelvis. However, this finding should be interpreted with caution because the differences were not significant, though the moderate effect size decreasing muscle activity of *gluteus medius* utilizing poles and the significant relationship between activation of *gluteus medius* with mediolateral margins of stability using the elbow technique.

Another interesting outcome regards the decrease of margins of stability calculated considering just feet contact, suggesting that the use of poles may effectively induce in subjects a feeling of safeness so that they can afford a larger lateral sway. Therefore, the use of poles has potential application for elderly population where the width steps is a critical parameter related to risk of falls (Hausdorff, 2005). Indeed, gait mobility in real/irregular context, the general balance should be a challenging motor task, particularly in elderly individuals where a decreased coordination between scapular and pelvis girdles is observed (Van Emmerik et al., 2005). This impairment in scapular and pelvis counter-movements influences dynamical stability, therefore the NW has potential to compensate for the increased trunk rigidity during walking in older people. We suggest that future studies should evaluate the effects of NW training on trunk coordination and dynamical stability in people with impaired balance and functional mobility. Recent evidence has shown improvements on functional mobility in individuals with Parkinson's disease and older people after NW training (Bombieri et al., 2017; Gomeñuka et al., 2019).

4.3. Limitations and perspectives

The present study analyzed only one speed of locomotion in controlled experimental conditions. We are aware that speed affects margins of stability and the trunk coordination and the additional effect of poles utilization on these parameters has not been yet investigated. These aspects together with the high level of skill of our subjects in using the poles while walking, however, limit the possibility to generalize the results of the present study to other walking speeds or populations. Future studies should take into account the margins of stability and coordination parameters in realistic/outdoor context to confirm these findings.

5. Conclusion

In conclusion, we found that NW and pole walking using predominantly elbows clearly have larger mediolateral margins of stability than walking, decreasing moderately the muscular engagement of *gluteus medius*. The increased dynamical stability is accompanied by a more stable control of the trunk rotational movement, thus suggesting the NW as an effective exercise intervention.

Conflict of interest

All authors have no conflict of interest and no further financial disclosure to make.

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Tables

Table 1 - Sample characterization showing mean and confidence interval (95% CI) for age, height, body mass, and body mass index.

Variable	**Mean (95% CI)**
Age (years)	39 (21 to 54)
Sex (f/m)	5 / 6
Height (cm)	171 (163 to 187)
Body mass (kg)	63 (51 to 76)
Body mass index (kg/m^2)	21.5 (18.3 to 24.3)

Note: f: females, m: males.

Table 2 - Mean, standard-deviation and statistical significance of stride length, EMG, range of girdle and joint motion, intergirdles coordination, and margins of stability between conditions walking, Nordic walking, and pole walking with elbows.

	Walking	**Nordic walking**	**Pole walking with elbows**
Stride length (m)	1.57 ± .06	1.78 ± .12†	1.64 ± .08†
EMG - *gluteus medius* (%)	25.3 ± 11.5	19.2 ± 7.1	17.7 ± 5.9
Range of joint motion sagital (degrees)			
Ankle	31.2 ± 4.7	32.9 ± 9.0	32.2 ± 7.0
Knee	63.0 ± 3.4	59.3 ± 6.5	63.0 ± 4.0
Hip	36.0 ± 3.0	42.6 ± 7.9†	39.9 ± 3.2
Shoulder	48.5 ± 1.6	45.7 ± 7.6	22.1 ± 5.6†‡
Elbow	41.6 ± 11.0	42.5 ± 11.7	46.9 ± 7.2
Range of girdle motion transverse (degrees)			
Scapular	7.8 ± 3.2	9.0 ± 4.5	4.0 ± 1.5†‡
Pelvis	17.9 ± 4.8	24.1 ± 9.5	17.6 ± 6.0
Continuous relative phase angle (degrees)			
all contact	1.4 ± 2.7	-2.5 ± 2.6†	-.6 ± 2.2‡
contact 0-20%	-6.1 ± 3.0	-4.9 ± 4.8	-5.5 ± 2.2
contact 20-50%	-1.6 ± 3.5	-7.4 ± 3.5†	-3.0 ± 2.6‡
contact 50-80%	4.5 ± 2.3	-1.2 ± 5.0†	1.8 ± 2.1
contact 80-100%	6.8 ± 1.9	4.7 ± 3.6	4.8 ± 1.5
Continuous relative phase variability (degrees)			
total stance	.9 ± .3	1.1 ± .3	.7 ± .1‡
loading response	1.0 ± .3	1.2 ± .6	.7 ± .2‡
mid-stance	1.0 ± .4	1.1 ± .3	.7 ± .2†‡
terminal stance	.8 ± .4	1.0 ± .3	.6 ± .2‡
push-off	.8 ± .2	1.3 ± .5†	.7 ± .1‡
Phase difference (degrees)	154.1 ± 23.9	117.8 ± 38.8	108.4 ± 54.6†
Margins of stability (cm)			
Anterior-posterior considering poles	-	-10.1 ± 5.5	-9.0 ± 6.7
Anterior-posterior body	-7.7 ± 5.5	-10.0 ± 5.4	-8.9 ± 6.7

Mediolateral considering poles	-	13.8 ± 3.8†	11.6 ± 3.6†
Mediolateral body	8.6 ± 1.1	7.9 ± 1.4	8.3 ± 1.1

Note: Subphases of continuous relative phase (CRP): total stance – CRP angle at all contact, loading stance – CRP angle at contact 0-20%, mid-stance – CRP angle at contact 20-50%, terminal stance – CRP angle at contact 50-80%, push-off – CRP angle at contact 80-100%; † Significant at the .05 probability level relative to Walking condition; ‡ Significant at the .05 probability level relative to Nordic walking condition.

Table 3 - The effect sizes (Hedge's g and 95%CI) and significance level (p) of Bonferroni's tests.

	Walking – Nordic walking		**Walking - Pole walking with elbows**		**Pole walking with elbows - Nordic walking**	
	Hedge's g	**p**	**Hedge's g**	**p**	**Hedge's g**	**p**
Stride length	2.2 (1.1, 3.2)	.001	.9 (-.2, 1.8)	.195	1.4 (.5, 2.3)	.001
EMG - *gluteus medius*	-.6 (-1.5, .2)	.237	-.8 (-1.7, .0)	.149	.2 (-.6, 1.1)	.743
Range of girdle motion transverse						
Scapular	.3 (-.6, 1.1)	1.000	-1.5 (-2.4, -.4)	.001	-1.4 (-2.1, -.8)	.001
Pelvis	.8 (-.1, 1.6)	.149	-.1 (-.9, .8)	1.000	-.8 (-1.6, .1)	.114
Range of joint motion sagital						
Ankle	.2 (-.6, 1.0)	1.000	.2 (-.7, 1.0)	1.000	.1 (-.7, .9)	1.000
Knee	-.7 (-1.4, .2)	.196	.0 (-.9, .9)	1.000	-.6 (-1.4, .2)	.188
Hip	1.1 (.3, 1.6)	.002	1.2 (.3, 2.2)	.101	.4 (-.4, 1.1)	.529
Shoulder	-.3 (-1.2, .6)	1.000	-3.0 (-4.2, -1.8)	.001	3.4 (2.5, 4.3)	.001
Elbow	.1 (-.8, 1.0)	1.000	.5 (-.4, 1.4)	.6	-.4 (-1.2, .4)	.871
Continuous relative phase angle						
total stance	-1.7 (-2.9, -.5)	.001	-.9 (-1.7, .1)	.145	-1.1 (-2.1, .0)	.015
loading response	.3 (-.5, 1.1)	1.000	.2 (-.6, 1.1)	1.000	.2 (-.7, 1.1)	1.000
mid-stance	-1.6 (-2.7, -.3)	.001	-.4 (-1.2, .5)	.948	-1.4 (-2.5, -.1)	.003
terminal stance	-1.4 (-2.3, -.5)	.001	-1.2 (-2.0, -.1)	.158	-.8 (-1.6, .1)	.091
push-off	-.7 (-1.5, .2)	.110	-1.1 (-2.0, -.2)	.142	-.0 (-1.0, .8)	1.000
Continuous relative phase variability						
total stance	.6 (-.2, 1.5)	.262	-.9 (-1.7, .1)	.083	1.5 (.8, 2.2)	.001
loading response	.2 (-.6, 1.1)	1.000	-1.0 (-1.6, -.1)	.129	.8 (.1, 1.6)	.024
mid-stance	.0 (-.8, .9)	1.000	-1.0 (-1.9, -.1)	.026	1.2 (.3, 1.7)	.019
terminal stance	.5 (-.3, 1.4)	.400	-.3 (-1.1, .6)	.577	1.0 (.2, 1.7)	.015
push-off	1.2 (.4, 2.1)	.001	-.5 (-1.4, .3)	.589	1.6 (.9, 2.5)	.001
Phase difference	-1.1 (-2.0, -.2)	.074	-1.1 (-2.1, -.2)	.022	.2 (-.7, 1.2)	1.000

Margins of stability						
anterior-posterior poles	-.5 (-1.4, .4)	.622	-.3 (-1.2, .6)	1.000	.2 (-.8, 1.0)	1.000
anterior-posterior body	-.4 (-1.3, .5)	1.000	-.2 (-1.1, .6)	1.000	-.2 (-1.0, .7)	1.000
mediolateral poles	1.8 (.7, 3.1)	.001	1.1 (.4, 1.8)	.044	.6 (-.4, 1.5)	.222
mediolateral body	-.5 (-1.4, .3)	.494	-.2 (-1.1, .6)	1.000	-.3 (-1.2, .5)	1.000

Note – Subphases of continuous relative phase (CRP): total stance – CRP angle at all contact, loading stance – CRP angle at contact 0-20%, mid-stance – CRP angle at contact 20-50%, terminal stance – CRP angle at contact 50-80%, push-off – CRP angle at contact 80-100%; poles – margins of stability considering poles; body – margins of stability considering just body (even using poles).

Figure legends

Figure 1 - The superior panel shows the EMG and stride length data in a multi-group (walking, W, Nordic walking, NW, and pole walking with elbows, elbow technique) Cumming estimation plot with multiple two-group comparisons plotted together. The lower panel shows the effect sizes (Hedges' g) with mean differences plotted as bootstrap sampling distributions, the mean difference is depicted as a dot, and the 95% confidence interval is indicated by the ends of the vertical error bars.

Figure 2 - Characteristics of continuous relative phase (CRP) angle. Ensemble-averaged (mean+SD) CRP angle of 5 pairs of joints and girdles plotted vs. normalized gait cycle for walking (W), Nordic walking (NW), and pole walking with elbows (elbow technique). Note a shift of the scapular-pelvis CRP angle (inferior panel) to NW (orange curve) in comparison to W (blue curve) and elbow technique (green curve).

Figure 3 - The individual data of phase difference between scapular and pelvis girdles reversion for walking (W, white square), Nordic walking (NW, black circles), and pole walking with elbows (elbow technique, white circles). Values close to 180 degrees indicate an out-of-phase/dissociate coordination and values close to 0 degree denote an in-phase/*en bloc* coordination.

Figure 4 - The superior part of each panel shows the margins of stability data in the anterior-posterior (AP) and mediolateral directions calculated using poles (POLES + BODY, left panels) or only body (BODY ONLY, right panels), with a multi-group (walking, W, Nordic walking, NW, and pole walking with elbows, elbow technique) Cumming estimation plot, with multiple two-group comparisons plotted together. The

lower part of each panel shows the effect sizes (Hedges' g) with mean differences plotted as bootstrap sampling distributions, the mean difference is depicted as a dot, and the 95% confidence interval is indicated by the ends of the vertical error bars.

Figure 5 - Correlation between delta *gluteus medius* activity and delta lateral margins of stability. The left panel shows the correlation between muscular activity and lateral stability based on these values subtracted between walking and Nordic walking conditions. The right panel shows the correlation between muscular activity and lateral stability based on these values subtracted between walking and elbow technique conditions.

Supplementary material

Supplementary material 1 - Checklist of STROBE.

Supplementary material 2 - Sampling size calculation from http://hedwig.mgh.harvard.edu/sample_size/js/js_crossover_quant.html.

Supplementary material 3 - Description of data analysis in details.

Supplementary material 4 - Individual dataset.

Supplementary material Figure 5 - Timecourse of elbow, shoulder, hip, knee, and ankle joint motion at sagittal plane, and timecourse of scapular and pelvis girdle motion at transverse plane averaged as a function of normalized stride from 1 subject during treadmill Nordic walking at 5.5 km.h^{-1}.

Supplementary material Figure 6 - Continuous relative phase angle from elbow-shoulder, shoulder-hip, hip-knee, knee-ankle joints at sagittal plane, and scapular and pelvis girdles at transverse plane divided by stride and averaged as a function of normalized stride from 1 subject during treadmill Nordic walking at 5.5 $km.h^{-1}$.

Supplementary material Movie 7 - Movies showing the margins of stability along stride for walking (7a), Nordic walking (7b) and pole walking with elbows (7c).