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Load dynamics of joints in Nordic walking

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Abstract

Recent years have seen a worldwide increase in people participating in Nordic walking (NW), with a heavy concentration in Northern Europe. This trend has led to abundant research in NW, which has the potential to reduce the load of the joints because poles are used during walking, and walkers may distribute part of their weight to the poles. A high exercise effect for NW is recognized now, and various studies are performed in the past. However, there are few studies focused on the various joint loads for NW. Therefore, as for examining having joint load reduction effect or not of the NW, it is with an important element judging the right or wrong of the application to everyday life of the NW for patients with joint disease and elderly people.The purpose of this study is to compare the joint load (lumbar spine, hip, knee and ankle joints) for NW to ordinary walking (OW) on a level surface and for going up and down stairs. Five healthy participants were asked to conduct NW and OW on a level surface and going up and down stairs equipped with force platforms. 3D inverse dynamics was used to calculate joint reaction force and joint moment in the lower limb joints. Then, the joint forces (compression and shear) at each of the lumbar spine, hip, knee and ankle joints were calculated using the Software for Interactive Musculoskeletal Modeling (SIMM). It was found that NW reduces the load of the lumbar spine and lower limb joints compared with OW on a level surface and going up stairs, but not going down stairs.

Keywords: Nordic Walking; joint loads; lumbar spine; lower limb joints

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1. Introduction

Nordic walking (NW) is an excellent mode of exercise because no difference in exertion rate is perceived even though energy expenditure is greater with NW than with ordinary walking (OW) [1]. Another supposed advantage of NW that has attracted interest is the reduced load on the lower limb joints, and the popular view of NW is that load on the lower limb joints during walking is reduced. This is not an unreasonable supposition, given that upper-body muscle action is greater in NW than OW [2], and the International Nordic Walking Association (INWA) initially advocated NW as effective in reducing the load on the lower limb joints. Willson *et al.* [3] reported from a study on the use of trekking poles that when the poles strike the ground while walking, the impact disperses, thus reducing ground reaction force on the knee joints in comparison to OW. Research into the load on the lower limb joints during NW has yielded contradictory results: some studies have reported that NW reduces load on the lower limb joints [4], while others have reported that NW increases the load. Even when NW is found to reduce the load, no agreement has been seen among studies over the degree of load reduction. While study of lower-limb joint load in NW has been conducted, there are no papers focusing on the load in the lumbar spine during NW, even though the number of patients with lumbar vertebrae disease represented by herniated intervertebral disks is increasing rapidly. Furthermore, there is the need for people to walk uphill, downhill and up and down stairs. On stairs, the load of the lower limb joints during OW increases 5-8 times compared with a level surface. It is difficult for patients with lower extremity weakness and elderly people to go up and down stairs. Therefore, in examining the joint load reduction effect of NW, we want to examine its usefulness in the everyday life of patients with joint disease and elderly people. Thus, the present study aims to undertake a kinematic analysis of NW and OW on a level surface and going up and down stairs.

2. Methods

2.1. Participants

Participants comprised five elderly people (age, 67.3 ± 1.63 years; height, 165.1 ± 3.12 cm; weight, 64.5 ± 2.25 kg). All participants fully understood the study objectives and methods and gave consent prior to participating. Also, all participants were experienced practitioners of NW as daily exercise.

2.2. Experimental condition

The track was 10-m long with a level surface and two force platforms (OR6-7, 50.8 ± 46.4 cm; AMTI, MA USA) placed at the midpoint. When walking over the force platforms during NW, participants were required to step on the left-hand force platform with the left foot and to strike the right-hand force platform with the pole held in the right hand as shown in Figure 1(a). During OW, participants stepped on the left-hand force platform with the left foot. The speed of NW was 4.52 ± 0.21 km/h and OW was 4.50 ± 0.22 km/h; the stride length of NW was 154.7 ± 5.31 cm and OW was 153.0 ± 2.06 cm. The stairs used are shown in Figure 1(b). All participants were asked to conduct NW and OW going up and down stairs equipped with force platforms (TF-4060-A, 40.0 ± 70.0 cm; TEC GIHAN CO., LTD. JAPAN). The participants were instructed to walk by a method like that on the level surface (Figure 1(a)). Each participant performed 10 trials going up and down the stairs. Fifty data sets were collected in each condition. The step lengths were not considered to be restricted and the speed of going up and down the stairs was 2.38 ± 0.13 km/h and 2.42 ± 0.14 km/h respectively.

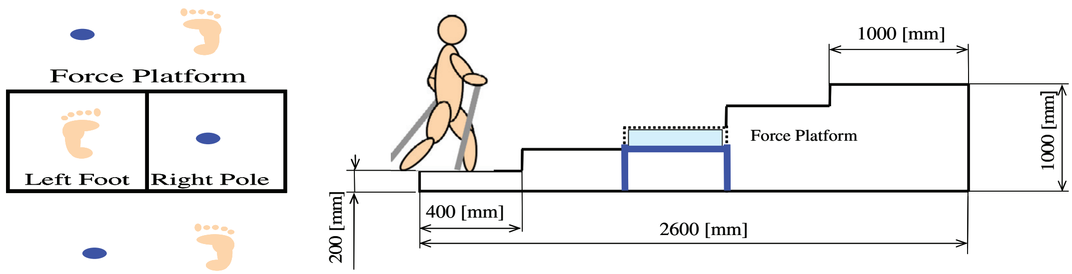

Fig. 1. (a) Style of walking; (b) structure of stairs

2.3. Motion analysis

To allow mechanical analysis of movement in each walking condition, 3D positional coordinates on the body of each participant were measured during movement. A 3D motion analysis system comprising 10 high-speed digital cameras (Eagle; Motion Analysis Corporation, CA USA) and the two force platforms described earlier were used. Data from the cameras and force platforms were measured at a sampling frequency of 120 Hz, and the devices were able to perform synchronized measurements.

3. Joint Load Evaluation Method

To investigate load on the lower limb joints, the present study focused on joint forces considered clinically important as forces causing pressure on the joints. Joint load was taken to be the compression force and shear force acting on the lumbar spine, hip, knee, and ankle joints. Joint forces were determined in accordance with inverse dynamics analysis by fitting a rigid-link model and a musculoskeletal model to motion data obtained from measurement of subject motion, ground reaction force data, and body measurement data. The method for calculating joint forces is given below.

3.1. Rigid-link model

The rigid-link model (Figure 2(a)) simulates the human body as a linkage mechanism comprising a number of rigid segments. A rigid-link model was made for each subject using their bodily parameters. Joint positions and ground reaction force data obtained during the experimental walking were mapped to this model, allowing joint moment and joint reaction force acting between segments of the link model during walking to be calculated over time. Joint reaction force and joint moment for each segment of the link model were determined using the Newton-Euler formulae (1) and (2) given below.

$$\mathbf{F}_\mathbf{P} = m\mathbf{a} - \mathbf{F}_\mathbf{D} - W \tag{1}$$

$$\mathbf{M}_\mathbf{P} = \frac{d\mathbf{H}}{dt}(\boldsymbol{\omega}, \dot{\boldsymbol{\omega}}, \mathbf{I}) - \mathbf{M}_\mathbf{D} - \mathbf{F}_\mathbf{P} \times \mathbf{P} - \mathbf{F}_\mathbf{D} \times \mathbf{D} \tag{2}$$

where m is the mass, $\mathbf{a}$ is the acceleration, $\mathbf{F_D}$ is the ground reaction force, $\mathbf{W}$ is the gravity, $\boldsymbol{\omega}$ is the angular velocity, $\dot{\boldsymbol{\omega}}$ is the angular acceleration, $\mathbf{I}$ is the inertia tensor, $\mathbf{H}$ is the angular momentum, $\mathbf{P}$ is the distance between the joint under consideration and the center of gravity of the segment, $\mathbf{D}$ is the distance between the joint not under consideration and the center of gravity of the segment, and $\mathbf{M_D}$ is the moment of the joint not under consideration.

3.2. Musculo-skeletal model

Joint forces were determined by adding the effects of working muscles on the segments to the rigid-link model. In the present study, musculo-skeletal models of the human body were used to gain an understanding of the muscle activity accompanying walking movement. A musculo-skeletal model (Figure 2(b)) was created for each subject on the basis of their bodily measurements using Software for Interactive Musculoskeletal Modeling (SIMM), produced by Motion Analysis (CA USA). The amount of muscle activity—the muscle tension resulting from muscle fibre contraction—needed for the musculo-skeletal model to recreate the joint moment and the joint motion behaviour was estimated. Joint forces were then calculated as shown in Formula (3) by adding the joint reaction force acting on the joint under consideration to the muscle tension, where $\mathbf{F}^{\mathbf{T}}$ is the tension in the tendon. Muscle tension for the musculo-skeletal model was estimated using a Hill-type muscle model.

$$\mathbf{F} = \mathbf{F_P} + \sum \mathbf{F_n^T} \tag{3}$$

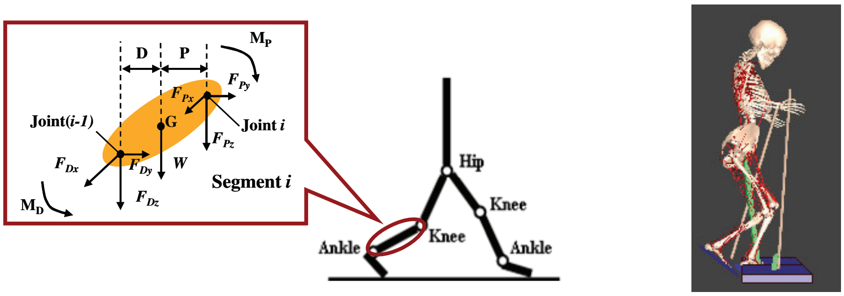

Fig. 2. (a) Rigid-link model; (b) musculo-skeletal model

3.3. Statistical analysis

The joint forces thus calculated for each subject were normalized by dividing by the body weight (bw) of the participant. *T*-test for paired data was used on differences between NW and OW. The alpha level for all statistical calculations was set at 0.05.

4. Results and Discussion

4.1. Flat level

Maximums of the joint forces on the L4 shear force (19.4%), the L5 shear force (27.7%), the hip compression force (8.6%), the hip shear force (10.0%), the knee compression force (12.1 %) and the knee shear force (28.0 %) were significantly lower in NW than in OW (Table 1).

From the results, NW was effective at reducing the joint forces of the L4 (shear), the L5 (shear), the hip joint (compression and shear) and knee joint (compression and shear) on the level surface. Here, we focus on the ground reaction force of the foot, which is an important factor influencing joint forces. Figure 3 shows the result that compared the ground reaction forces of OW with NW and the ground reaction force of the pole. From Fig. 3, the ground reaction force of the foot was lower in NW than OW while using the pole. Maximums of the ground reaction force of the foot in NW at 1.18 ± 0.22 N/bw and

OW at 1.28 ± 0.23 N/bw were significantly lower (P<0.05). NW therefore had the effect of joint load reduction by reducing mechanical load on joints.

Table 1. Joint forces on level surface

	NW	OW	P-value
Lumbar 1 compression force [N/bw]	0.92±0.29	0.96±0.25	0.68
Lumbar 1 shear force [N/bw]	0.20±0.14	0.19±0.07	0.67
Lumbar 2 compression force [N/bw]	0.97±0.28	1.01±0.12	0.60
Lumbar 2 shear force [N/bw]	0.21±0.11	0.20±0.05	0.73
Lumbar 3 compression force [N/bw]	0.97±0.29	1.00±0.12	0.76
Lumbar 3 shear force [N/bw]	0.24±0.08	0.29±0.04	0.08
Lumbar 4 compression force [N/bw]	0.98±0.30	0.98±0.12	1.00
Lumbar 4 shear force [N/bw]	0.29±0.06	0.36±0.05	<0.05
Lumbar 5 compression force [N/bw]	0.98±0.31	1.00±0.12	0.67
Lumbar 5 shear force [N/bw]	0.34±0.06	0.47±0.08	<0.05
Hip compression force [N/bw]	4.48±0.26	4.90±0.28	<0.05
Hip shear force [N/bw]	2.23±0.54	2.48±0.32	<0.05
Knee compression force [N/bw]	4.56±0.50	5.19±0.29	<0.05
Knee shear force [N/bw]	2.75±0.98	3.82±0.35	<0.05
Ankle compression force [N/bw]	5.96±1.19	6.43±0.28	0.16
Ankle shear force [N/bw]	1.39±0.68	1.42±0.27	0.83

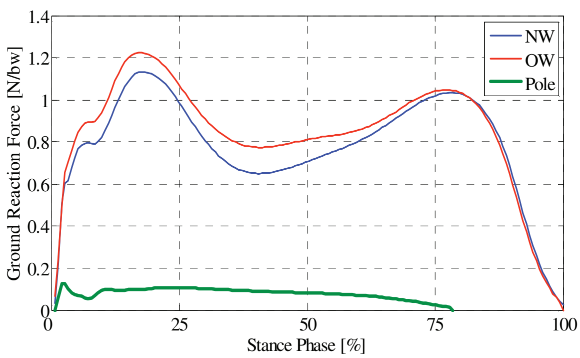

Fig. 3. Ground reaction forces on level surface

4.2. Up and down stairs

Going up the stairs, the maximums of the joint forces on the L1 shear force (22.2%), L3 shear force (9.3%), L4 shear force (8.0%), hip compression force (7.4%) and knee shear force (12.2%) were significantly lower in NW than in OW (Table 2). Going down the stairs, no significant difference was found between OW and NW in the maximum of each compression and shear joint force (Table 3).

Table 2. Joint forces in up stairs

	NW	OW	P-value
Lumbar 1 compression force [N/bw]	1.10±0.33	1.11±0.27	0.75
Lumbar 1 shear force [N/bw]	0.21±0.11	0.27±0.12	<0.05
Lumbar 2 compression force [N/bw]	1.11±0.32	1.11±0.27	1.00
Lumbar 2 shear force [N/bw]	0.25±0.11	0.27±0.10	0.10
Lumbar 3 compression force [N/bw]	1.12±0.31	1.10±0.27	0.86
Lumbar 3 shear force [N/bw]	0.29±0.12	0.32±0.08	<0.05
Lumbar 4 compression force [N/bw]	1.11±0.31	1.10±0.28	0.79
Lumbar 4 shear force [N/bw]	0.35±0.11	0.38±0.07	<0.05
Lumbar 5 compression force [N/bw]	1.10±0.32	1.09±0.30	0.75
Lumbar 5 shear force [N/bw]	0.41±0.11	0.44±0.07	0.08
Hip compression force [N/bw]	4.00±4.56	4.32±1.58	<0.05
Hip shear force [N/bw]	2.10±1.66	2.32±1.67	0.20
Knee compression force [N/bw]	4.03±1.72	3.81±1.42	0.26
Knee shear force [N/bw]	4.97±2.56	5.66±2.63	<0.05
Ankle compression force [N/bw]	4.34±1.15	4.35±0.53	0.95
Ankle shear force [N/bw]	0.99±1.02	0.88±0.37	0.53

Table 3. Joint forces in down stairs

	NW	OW	P-value
Lumbar 1 compression force [N/bw]	1.24±0.26	1.18±0.26	0.75
Lumbar 1 shear force [N/bw]	0.23±0.06	0.23±0.38	0.84
Lumbar 2 compression force [N/bw]	1.27±0.23	1.19±0.29	0.15
Lumbar 2 shear force [N/bw]	0.21±0.09	0.21±0.10	0.82
Lumbar 3 compression force [N/bw]	1.28±0.23	1.20±0.28	0.14
Lumbar 3 shear force [N/bw]	0.24±0.12	0.24±0.12	0.98
Lumbar 4 compression force [N/bw]	1.28±0.23	1.20±0.28	0.14
Lumbar 4 shear force [N/bw]	0.30±0.14	0.31±0.13	0.80
Lumbar 5 compression force [N/bw]	1.27±0.24	1.18±0.29	0.13
Lumbar 5 shear force [N/bw]	0.37±0.11	0.40±0.15	0.23
Hip compression force [N/bw]	4.09±0.99	4.19±1.06	0.57
Hip shear force [N/bw]	1.91±1.14	1.81±1.01	0.59
Knee compression force [N/bw]	4.47±0.92	4.39±0.86	0.69
Knee shear force [N/bw]	5.58±1.71	6.29±2.54	0.11
Ankle compression force [N/bw]	5.28±1.72	5.42±1.93	0.52
Ankle shear force [N/bw]	2.09±1.18	1.94±1.28	0.36

The ground reaction forces focused on the level surface. Figure 4 shows the result that compared the ground reaction forces of OW with NW and the ground reaction force of the pole going up and down the stairs. From Figure 4(a), the ground reaction force of the foot had less NW in comparison with OW going up the stairs. Maximums of the ground reaction force of the foot in NW at 1.20 ± 0.05 N/bw and OW at 1.24 ± 0.06 N/bw were significantly lower ($P < 0.05$). Going down the stairs, the ground reaction force of the foot was lower NW in comparison with OW. However, no significant difference was found between OW and NW in the maximum ground reaction force of the foot going down the stairs ($P = 0.09$). According to this, it was concluded there were significant differences in NW of joint forces going up or down stairs.

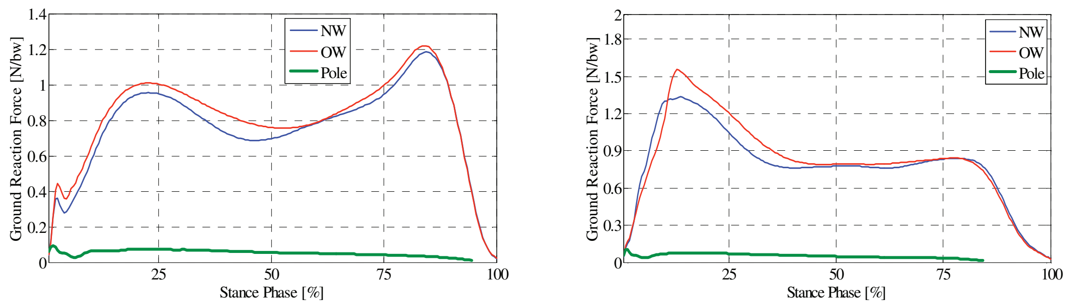

Fig. 4. (a) Ground reaction forces going up stairs; (b) ground reaction forces going down stairs

5. Conclusion

In this paper, NW and OW were compared regarding the joint forces, and the joint load reduction effect of NW was investigated.

(1) On level ground, NW had a load reduction effect on the L4 and L5 shear force, the hip compression and shear force, the hip shear and compression force and the knee shear force.
(2) Going up stairs, NW had a load reduction effect on the L1 and L3 and L4 shear force, the hip compression force and knee shear force.
(3) Going down stairs, NW had no load reduction effect in any joint.

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