Compared with walking (W), Nordic walking (NW) exhibits greater cardiopulmonary and cardiovascular benefits. Some authors conjecture that compared with W or running (R), NW imposes smaller mechanical loads on the musculoskeletal system. The purpose of the current study was to quantify any differences in joint loading of the lower extremities among NW, W, and R. Fifteen experienced adults participated. Kinematic and force measurements were combined using an inverse dynamics approach to yield joint moments. The results showed no biomechanical benefit of NW. Instead, NW involved greater knee joint loading just after heel strike compared with W. This was due to the longer steps and the higher sole angle during the first part of the stance phase. The sagittal and frontal plane moments were smaller for NW compared with R, but in the transverse plane, the ankle moments were greater in NW than in W or R. Based on these results, NW is not recommended as an exercise for persons who seek to reduce biomechanical loading of the lower extremities.

**Keywords:** kinematics, kinetics, joint loading

In the last few years, Nordic walking (NW) has rapidly increased in popularity in the field of fitness sports and still has a high market potential (Gustafsson, 2004). Furthermore, it is recommended as an alternative to running (R), as exercise for overweight people, and as rehabilitation for orthopedic patients with existing musculoskeletal problems of the lower limbs (Strunz, 2004). Numerous scientific studies revealed a higher cardiopulmonary and cardiovascular benefit for NW compared with walking (W; Church et al., 2002; Rodgers et al., 1995; Walter et al., 1996). Moreover, the nonscientific literature and the mass media claim that NW reduces the mechanical loads on the lower extremities (~30%) owing to joint unloading effects when using the poles during stance phase (Strunz, 2004). But, there is no scientific evidence for a reduction of mechanical loading and the benefit of level NW for rehabilitative purposes.

In the scientific literature, only a few serious biomechanical studies have been published investigating the differences in mechanical load between NW, W, and R. In this context, Brunelle and Miller (1998) found that, at the same speed, the vertical ground reaction forces during landing are higher for NW compared with W. This result has been confirmed by a study conducted by Rist et al. (2004). Jöllenbeck et al. (2006) as well as Thorwesten et al. (2006) also showed that there is no reduction of the vertical ground reaction force in NW compared with W. In addition, Hagen et al. (2006) found that, except for the second peak of vertical force, NW results in higher loading rates and horizontal forces compared with ordinary W. Furthermore, Franz et al. (2006) reported no differences between NW and W in knee external rotation moments and knee flexion moments. In contrast to W and NW, R, at the same speed, results in 30% greater vertical force and is characterized by higher knee loading (up to 40%) in comparison with NW (Schwameder & Ring, 2006).

Regarding downhill walking, NW does appear to provide benefits. Bohne and Abendroth-Smith (2007) examined the effects of hiking downhill using trekking poles while carrying external loads. They observed a
significant reduction for the sagittal plane moment at each of the joints in the lower extremity when the poles were used. In addition, Schwamender et al. (1999) showed that downhill walking with hiking poles compared with downhill walking without hiking poles leads to a significant reduction of vertical ground reaction forces, knee joint moments (sagittal plane) and tibiofemoral compressive and shear forces (12–25%). However, the subjects performed a 3-by-1 simultaneous pole technique (double-pole technique), where the touch-down of both poles occurred simultaneously as opposed to the diagonal technique, which is predominantly used in NW.

Owing to the lack of research, the biomechanical benefit of using the poles in level NW regarding preventive and rehabilitative aspects is questionable. Therefore, the purpose of this study was to investigate the biomechanical effects of using Nordic walking poles (with the diagonal technique) on the joint loading of the lower extremities compared with W and R based on kinematic and kinetic data. Specifically, does the use of the poles during NW lead to a reduction of mechanical load on the lower extremities compared with W and R?

Methods

Participants

Fifteen male adults (mean age = 31 years, $SD = 4.64$ years; mean body height = $1.77 \text{ m}$, $SD = 0.04 \text{ m}$; mean body mass = $77 \text{ kg}$, $SD = 7.59 \text{ kg}$) participated in this study. Subjects were experienced Nordic walkers with an average experience of 2 years and a mean training volume of 13 km per week. Most of them (10 out of the 15) were educated NW instructors. All subjects were rearfoot strikers and reported being free of any injuries.

Biomechanical Measurement

The study was performed in the biomechanical laboratory of Adidas in Scheinfeld, Germany. Kinematic data were collected using a 6-camera 3-dimensional Vicon System (Vicon, Oxford Metrics, Oxford, UK; sample rate: 200 Hz). The subjects were shod and reflective markers (14 mm diameter) were placed on standardized, constant defined locations on the pelvis, upper leg, lower leg, rearfoot, and forefoot (3 per segment; Figure 1). Kinetic data were collected using a Kistler force platform (Kistler, Winterthur, Switzerland; sample rate: 1000 Hz). A lower body model (Michel et al., 2004) was applied to determine joint centers and three-dimensional angles between segments. A static trial was used to calculate the “neutral-0 position” of the joints. The zero position of the foot was determined by 3 markers on the rearfoot setting up a coordinate system aligned with the floor. The model was programmed in Bodybuilder (version 3.6) and can be used with the commercial software Vicon-Workstation (version 4.6).

Procedure

After the subjects had completed a standardized questionnaire, their body weight was measured and reflective markers were attached. Subjects moved across the force platform in the middle of a 20-m runway at a controlled velocity of $2.0 \pm 0.2 \text{ m/s}$ for NW and W and $4.0 \pm 0.2 \text{ m/s}$ for R and wore the same conventional running shoe (Adidas Adistar Trail; size: 8.5 UK) during all trials. This relatively fast speed for NW and W was deliberately chosen to provoke the active use of the poles (NW) and the arms (W). Kinematic and kinetic data were collected for 5 valid trials for each subject and movement condition in random order after unrestricted warm-up. The NW trials were executed in the diagonal technique (Regelin & Mommert-Jauch, 2004) using the same NW pole (type Exel). The pole length was adapted for each subject based on body height ($2/3$ of the height; Regelin & Mommert-Jauch, 2004; Rist et al., 2004).

Biomechanical Calculations and Statistical Analysis

Missing frames were handled with a fill-gap procedure. The data were smoothed with a Woltring filter and using a spline smoothing (Woltring, 1991). Three-dimensional knee and ankle joint moments during the stance phase were calculated using an inverse dynamics approach. In accordance with Stefanyshyn and Nigg (1997) using the same method, the metatarsophalangeal (MTP) joint moments in the sagittal plane during stance phase were also determined. In this context, the center between the first and fifth MTP marker was chosen to represent the MTP center of rotation. This procedure is based on the assumption that the inertial forces acting on the phalanges can be neglected (Stefanyshyn & Nigg, 1997). The MTP moment was considered to be zero until the heel left the ground. Selected values (Figure 2) were determined from each trial and averaged for each condition and subject. The shape of distribution of the present sample was checked using the Kolmogorov–Smirnov test. Because a normal distribution was not completely confirmed in the current study, differences between the movement conditions were tested for significance using nonparametrical tests (Friedman and Wilcoxon). The $\alpha$ level was set to 0.05. Moreover, $p$ values between 0.051 and 0.100 were interpreted as statistical trends.

Results

Regarding the knee motion, the maximum knee joint angles in all three planes showed higher values for NW compared with W (Figure 2, Figure 3A). In the sagittal plane, the knee joint angles at touchdown ($t_d$) revealed significant differences between NW and W compared with R. For NW and W, the knee was more extended at touchdown (Figure 2). In the frontal plane, there was a trend for the maximum knee adduction angle (Figure...
Figure 1 — Placement of the markers.
The maximum ankle joint plantar flexion angle was significantly lower during R compared with NW and W (Figure 2).

The maximum MTP dorsiflexion angle occurred during push-off and exhibited significantly higher values for NW and W compared with R (Figure 2).

With regard to the segment movement with reference to the global coordinate system (GCS), the significantly higher sole angle of the foot in NW at touchdown ($\delta_0$; Nigg, 1986, Figure 4) led to a significantly higher

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Plane / direction</th>
<th>NW mean $\pm$ SD</th>
<th>W mean $\pm$ SD</th>
<th>R mean $\pm$ SD</th>
<th>NW vs. W p-level</th>
<th>W vs. R p-level</th>
<th>NW vs. R p-level</th>
<th>W vs. R p-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip joint angle - flexion at touch down $\beta_0$ [°]</td>
<td>sagittal</td>
<td>49.12 5.62</td>
<td>45.90 5.74</td>
<td>41.68 6.13</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Knee joint angle - flexion at touch down $\beta_1$ [°]</td>
<td>sagittal</td>
<td>-1.31 6.78</td>
<td>-0.67 7.19</td>
<td>2.71 5.96</td>
<td>0.776</td>
<td>0.001</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Knee joint angle - max. flexion [°]</td>
<td>sagittal</td>
<td>22.27 0.00</td>
<td>20.01 7.75</td>
<td>34.53 7.37</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Range of Motion - flexion/extension [°]</td>
<td>sagittal</td>
<td>24.70 3.13</td>
<td>22.97 3.31</td>
<td>32.65 4.22</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Knee joint angle - max. adduction [°]</td>
<td>frontal</td>
<td>13.41 6.10</td>
<td>9.91 5.07</td>
<td>12.90 5.64</td>
<td>0.001</td>
<td>0.221</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Knee joint angle - max. internal rotation [°]</td>
<td>frontal</td>
<td>17.82 11.80</td>
<td>17.07 12.06</td>
<td>1.39 5.76</td>
<td>0.334</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Range of Motion - internal/external rotation [°]</td>
<td>transverse</td>
<td>45.32 10.70</td>
<td>42.53 11.33</td>
<td>23.31 6.15</td>
<td>0.019</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Ankle joint angle - dorsiflexion at touch down $\beta_2$ [°]</td>
<td>sagittal</td>
<td>-0.11 4.53</td>
<td>0.01 4.78</td>
<td>2.98 7.03</td>
<td>0.570</td>
<td>0.017</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>Ankle joint angle - max. plantarflexion [°]</td>
<td>sagittal</td>
<td>-16.59 5.98</td>
<td>-15.00 5.55</td>
<td>-6.50 2.98</td>
<td>0.070</td>
<td>0.001</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Ankle joint angle - max. dorsiflexion [°]</td>
<td>sagittal</td>
<td>5.51 4.74</td>
<td>6.93 4.62</td>
<td>15.23 5.42</td>
<td>0.410</td>
<td>0.001</td>
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</tr>
<tr>
<td>Ankle joint angle - max. eversion ($\beta_{max}$) [°]</td>
<td>frontal</td>
<td>4.51 2.61</td>
<td>3.61 2.71</td>
<td>7.04 3.34</td>
<td>0.005</td>
<td>0.003</td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Ankle joint angle - max. adduction [°]</td>
<td>transverse</td>
<td>-5.61 7.07</td>
<td>-5.61 7.24</td>
<td>-8.37 7.32</td>
<td>0.589</td>
<td>0.001</td>
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</tr>
<tr>
<td>MTP joint angle - max. dorsiflexion [°]</td>
<td>sagittal</td>
<td>-25.60 3.47</td>
<td>-25.49 4.56</td>
<td>-19.48 3.40</td>
<td>0.755</td>
<td>0.001</td>
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<td></td>
</tr>
</tbody>
</table>

Figure 2 — Kinematic and kinetic data. Note. gcs: segment movement with reference to the global coordinate system; NW: Nordic walking; W: walking; R: running; n = 15.
sole angle velocity ($\dot{\delta}_s$) during NW compared with W (Figure 2, Figure 5A). For R in comparison with NW and W, a significantly higher inversion angle of the foot at touchdown ($\gamma_0$) was noted in the frontal plane (Figure 2, Figure 5B). Similar to the maximum eversion ankle angle (calcaneus with reference to shank; $\beta_{\text{max}}$), the maximum eversion angle (calcaneus with reference to GCS; $\gamma_{\text{max}}$) showed lower values for W compared with NW and R. The higher eversion angle contributed to the significantly higher ROM ($\gamma_{\text{ROM}}$) in NW (mean difference 17%) and R (mean difference 58%) compared with W (Figure 2). In the transverse plane, the maximum exorotation of the foot (Figure 2, Figure 5C) was significantly higher in NW compared with W (mean difference 12%) and R (mean difference 26%).

Regarding the vertical forces and the locomotion patterns of NW and W, the first force peak (landing) revealed no significant difference and the second force peak (push-off) only exhibited a statistical trend ($p = .088$) for lower forces during NW. The vertical loading rate was higher for NW than for W (Figure 2). Vertical ground reaction forces in R were significantly higher than in NW and W (Figure 2, Figure 6A). The fore–aft ground reaction forces data (Figure 6B) indicated a significantly lower first force peak (braking) during W and significantly lower forces during propulsion (second peak) compared with NW (Figure 2). Regarding the range of the mediolateral ground reaction forces, there was only a statistical trend ($p = .061$) for higher mediolateral ground reaction forces in NW compared with W (Figure 2).

The joint loading of the lower extremities indicated no reduction for NW. The analysis of the knee extension moment (Figure 7A) showed a significantly higher moment for NW compared with W (mean difference 11%; Figure 2). The highest moment in the sagittal plane was reached in R. For NW and W, the maximum knee extension moment occurred just after heel strike, and during midstance for R. The knee joint moments in

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**Figure 3** — (A) Average knee joint angles in the sagittal plane ($n = 15$). (B) Average knee joint angles in the frontal plane ($n = 15$). (C) Average knee joint angles in the transverse plane ($n = 15$).
the frontal plane (Figure 7B) revealed a significantly higher maximum abduction moment just after heel strike for NW compared with W (mean difference 12%). During push-off, there were no significant differences between NW and W in frontal plane knee moments. The highest moment was reached in R during midstance (Figure 2). The maximum knee external rotation moment (Figure 7C), which occurred during push-off phase, was significantly higher in NW compared with W. Surprisingly, the maximum knee external rotation moments for NW were as great as for R (Figure 2).

Just after heel strike, the ankle dorsiflexion moments in the sagittal plane were significantly higher for NW and W compared with R. The ankle plantar flexion

Figure 5 — (A) Average foot angles in the sagittal plane (n = 15). (B) Average foot angles in the frontal plane (n = 15). (C) Average foot angles in the transverse plane (n = 15).

Figure 6 — (A) Average vertical ground reaction force (GRF) data (n = 15). (B) Average anterior-posterior plane GRF data (n = 15).
Inverse Dynamic Analysis of the Lower Extremities

Moment did not show significant differences between NW and W. Not surprisingly, the ankle plantar flexion moment for R was significantly greater than for NW or W (Figure 2, Figure 8A). The maximum ankle inversion moment just after heel strike was significantly higher for W compared with NW. In the push-off phase, the significantly lowest ankle eversion moment was determined for R (Figure 2, Figure 8B). The ankle joint moments in the transverse plane (Figure 8C) revealed a significantly higher maximum abduction moment for NW compared with W (mean difference 7%) and R (mean difference 52%; Figure 2).

Regarding the maximum MTP plantar flexion moment in the push-off phase, the pole use did not affect joint loading in the MTP region compared with W. Owing to the higher velocity, the highest plantar flexion moment occurred in R (Figure 2).

Discussion

The results of this study clearly show no reduction in joint loading for NW (diagonal technique) compared with W. A probable cause for the lack of reduction in joint loading is that the poles are primarily used during the push-off phase, whereas maximal joint loads occur earlier in the stance phase (Kleindienst et al., 2006).

The higher knee extension moment in NW compared with W can be explained by the higher sole angle and hip joint angle at touchdown (t0) in the sagittal plane (Figure 2). In the frontal plane, the significantly higher maximum knee abduction moment just after heel strike for NW compared with W is mainly caused by the higher maximum knee adduction angle. Owing to the fact that the knee and ankle joint angles at touchdown in the sagittal plane are not significantly different in NW compared with W, the longer step length and the resultant higher sole angle at touchdown (Rist et al., 2004) can be considered as further reasons for the higher maximum knee abduction moment. The highest maximum knee external rotation moment in NW, which occurs in the push-off phase, is caused by the higher maximum internal rotation angle during NW compared with R. However, the main reason for this higher moment is probably the higher maximum exorotation of the foot during push-off for NW compared with W and R. Significant differences for this knee external rotation moment are only indicated between NW and W, which can be explained by the high standard deviation in R (Figure 2). Franz et al. (2006) also did not observe a reduction of knee external rotation moment for NW compared with W.

In comparison with NW and W, the lower ankle dorsiflexion moment in the sagittal plane during landing in R can be explained by the lower sole angle at touchdown and the lower maximum ankle plantar flexion

Figure 7 — (A) Average knee joint moments in the sagittal plane (n = 15). (B) Average knee joint moments in the frontal plane (n = 15). (C) Average knee joint moments in the transverse plane (n = 15).
tion force and impulse of the walking poles. The data show that the vertical reaction forces measured in the walking poles are small and the peak of the highest forces does not overlap with the time to peak of the maximum vertical reaction forces of the foot. The second force peak (push-off) only exhibits a statistical trend for lower forces during NW compared with W, which can be explained by the use of the poles (Kleindienst et al., 2006). The higher vertical loading rate in NW is caused by the higher sole angle velocity, the higher sole angle, and probably the resultant reduction of contact area at touchdown (Kleindienst et al., 2006). The significantly lower fore–aft ground reaction forces data regarding the first force peak (braking) during W compared with NW are also caused by the lower sole angle at touchdown (Kleindienst et al., 2006). The higher mediolateral ground reaction forces in NW and R could be the cause of greater knee moments, respectively, during landing and during midstance in the frontal plane.

The higher maximum ankle eversion angle ($\beta_{\text{max}}$) in NW compared with W can cause stress in the knee joint (runner’s knee; Novacheck, 1998) and may lead to an acroarthritis of the Achilles tendon (Ingenhoven & Gierse, 1992). However, this angle is less than that observed during running.

In comparison with W, the higher hip joint angle at touchdown and the higher sole angle in NW are caused by the longer steps (Regelin & Mommert-Jauch, 2004; Rist et al., 2004; Schwitz et al., 2003; Willson et al., 2001). These angles explain the higher maximum knee extension moment, the higher maximum knee abduction moment in the landing phase, and the higher maximum fore–aft force peak during braking, as well as the higher vertical loading rate in NW compared with W. All these parameters occur during landing/braking, and hence they can be caused by the significantly higher hip and sole angle at touchdown. It should be noted that the knee and ankle joint angles at touchdown in the sagittal plane are not significantly different in NW compared with W. Moreover, the touchdown inversion angle in the frontal plane only shows a statistical trend between NW and W. These findings lead to the conclusion that the longer step length and the resultant higher hip and sole angle during NW are the primary causes for the changes in kinetics and kinematics just after heel strike. The highest inversion angle at touchdown in R and the higher velocity lead to a higher eversion velocity compared with NW and W. The higher maximum exorotation of the foot in the push-off phase during NW could be the reason for the high knee joint moments in the transverse plane for this locomotion pattern.

In summary, compared with W, NW using the diagonal technique does not reduce the joint loading of the lower extremities based on kinematic and kinetic data in general. In the transverse plane, the maximum ankle joint moments during NW are even higher than in R. Regarding R, it is well known that increased knee joint moments in the frontal and transverse plane are directly linked to the incidence of patellofemoral pain syndrome (Stefanyshyn et al., 1999). Such knee joint loads may...
also contribute to patellofemoral pain syndrome in NW and W. Therefore, it is necessary to conduct prospective epidemiological studies to analyze the influence of lower extremity joint moments on the appearance of specific disturbances.

Based on the results of this study, the popular recommendation of NW as a rehabilitation training concept for overweight people and orthopedic patients with existing musculoskeletal problems of the lower limbs compared with W has to be reconsidered. The typical NW technique involves long steps; an extended knee and a higher sole angle at heel strike contribute to these increased joint loads. Therefore, a modified technique, which avoids these specific movement criteria, could lead to a considerable load reduction.

Acknowledgments
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