Optokinetic analysis of gait cycle during walking with 1 cm- and 2 cm-high heel lifts

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Abstract

The use of orthotic heel lifts is proposed in many cases of Achilles tendon disorders as a first-line or conservative treatment. The use of heeled shoes induces a plantar flexion of the ankle joint with a consequent decrease in the tension forces acting onto the triceps surae. The question to address is how high must the heel be? Gait cycle using 1 cm- and 2 cm-high heel lifts was examined. Each measurement included kinetic and kinematic data on angular variation and moments and power at the hip, knee and foot. The study included 14 healthy subjects (5 males, 9 females) between 20 and 35 years of age. The data provided by the analysis of the force plate curve showed a statistically significant change in some parameters (plate forces, knee moments) which were deemed useful in the analysis of load transfer modalities. A very significant decrease ($p = 0.0001$) was found in the amplitude of the curve expressing the force produced by the whole limb in response to ground reaction forces. This is expressed by a decrease in minimum values, suggesting a lower degree of energy absorption at heel strike, as well as maximum values reflecting the amount of energy generated at push off. This might suggest that by reducing energy absorption by the whole limb a 2-cm heel lift would have a protective effect for those muscles that are most significantly involved in this function, such as the tibiotarsal complex (triceps surae) and the knee complex (rectus femoris).

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1. Introduction

The use of orthotic heel lifts is proposed in many cases of Achilles tendon disorders as a first-line or conservative treatment. In the first case this is done to address the problem of a limited function of the ankle joint while the aetiology of the disorder is still unknown. In the second case the purpose is to protect the tendon in view of future surgery or long enough to allow for complete functional recovery.

The use of heeled shoes induces a plantar flexion of the ankle joint with a consequent decrease in the tension forces acting onto the triceps surae. The question to address is how high must the heel be to ensure that its disadvantages do not outweigh its benefits?

Several studies have analyzed the effects of heeled shoes, and more specifically their impact on gait dynamics and the possible repercussions on lower limb structures.

It is widely documented that walking with heeled shoes has several important implications on the tibiotarsal joint where this causes a significant increase in plantar flexion during the gait cycle [1,2] with consequent higher incidence of ankle trauma [3], changes in foot stability and earlier muscle fatigue [4].

In addition, the evidence gathered has also shown other effects of heeled shoes, such as different pressures of the foot on the ground with an increased load at the level of the midfoot and under the calcaneus. Conversely, there is a significant decrease in the forefoot contact area and maximum force with the peak pressure increasing by approx. 30% [5].

These modifications result, among others, in a change in ground reaction forces with an increase of its vertical component (Fz), centre of pressure deviation (medial/lateral) and the angle of the sagittal plane ground reaction force vector [6].
Table 1: Cork lifts specifications.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Cork conglomerate fixed by polyurethane glue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granules Average Diameter</td>
<td>Between 1 and 2 mm</td>
</tr>
<tr>
<td>Specific weight</td>
<td>265 kg/m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>10 mm cork lifts</th>
<th>20 mm cork lifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>72 mm</td>
</tr>
<tr>
<td></td>
<td>77 mm</td>
</tr>
<tr>
<td>Max Width</td>
<td>55 mm</td>
</tr>
<tr>
<td></td>
<td>55 mm</td>
</tr>
<tr>
<td>% inclination</td>
<td>12.7%</td>
</tr>
<tr>
<td>Degree of inclination</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>13.6</td>
</tr>
</tbody>
</table>

One can logically assume that the use of heeled shoes has its major effects on the hindfoot, with significant changes in angular variations and moments [7]. In fact, this is the area where the most significant postural adjustments occur, with minor changes in the pelvis and the trunk position [1] and more important modifications at the level of the knee, where the use of moderately high heels might allegedly cause higher rates and/or progression of arthritis [8,9].

However, as the data reported in literature concern the use of rather thick heel lifts [1,2,4,8], high heels (over 5 cm and up to 7.5 cm) or moderately high heels (3.8 cm), the authors have investigated the effects of low heel lifts (1 cm and 2 cm) commonly used in orthopaedic practice.

In particular, the study was focused on the following parameters: ankle and knee moments and variations of the forces expressed at the hip, knee and ankle joints in the phases of initial weight bearing and load transfer (0–15%, 15–40% of the gait cycle); literature suggests that such factors are helpful for an assessment of the effectiveness of a treatment based on heeled orthoses.

2. Materials and methods

Gait cycle using 1 cm- and 2 cm-high heel lifts was examined. The features of the heel lifts are exposed in table (Table 1). Each measurement included kinetic and kinematic data on angular variation and moments and power at the hip, knee and foot.

Such data were then compared with those of subjects walking without heels. The studied included 14 healthy subjects (5 males, 9 females) between 20 and 35 years of age (26.5 ± 5.21) with no clinical signs of subtalar joint hyperpronation, normal body weight (BMI between 18.5 and 24.9) and average height (168.46 ± 4.10 cm).

2.1. Assessment setting

The kinetic and kinematic analysis was performed using a Qualisys Motion Capture System with 6 Vicon Pro Reflex Motion Capture infrared cameras with a 120-Hz measurement frequency, which followed the movement of 18 passive markers simultaneously.

Such kinematic data were then coupled with kinetic data collected synchronically to markers' images measuring ground reaction forces through two AMTI force plates located at the centre of the walkway (i.e., a 10-m-long and 1.3-m-wide platform).

The software used for motion capture, the assignment of markers with body segment reconstruction and data processing were: Qualisys Q Trac Capture version 2.57, Q Trac View version 3.00 and Q Gait version 2.0.

2.2. Markers and marker positioning

The motion capture system used 18 passive markers fixed with double-sided tape onto the following anatomical landmarks on the subject’s skin in accordance with the “skin” protocol: spinous process of the 12th thoracic vertebra and the sacrum; bilaterally: upper surface of the acromion, anteroinferior iliac spine, suprapatellar position (along the central axis of the patella 1 cm above the upper margin at the level of the rectus femoris tendon), laterally to the knee joint line, at the centre of the tibial tubercle, above the lateral malleolus, at the hindfoot behind the calcaneus and on the toes between the second and third metatarsal bones (Fig. 1).

2.2.1. Fixing lifts to the hindfoot

The lift was put under the heel and fixed with a specific eudermic traction-resisting taping band aid, in order to ensure harmony with the foot movements.

The fixing has been done on the front of the midfoot until the line of Chopart in order to avoid longitudinal slipping; on the back at rear calcaneal level, so that tibia-tarsal articular range would not be harmed; next to the Achille’s tendon connection.

Cross stabilization was granted by a semicircular fixing which included back and middle calcaneus as well as lateral cuboid.

Fig. 1. Lower limb markers located on the protocol landmarks.

1 All subjects turned out to have normal muscular force and lower limbs articular ROM; they have been evaluated through the Clarkson (2002) muscular and articular exam [10].
2.3. Assessment procedure

Each measurement session began with the calibration of the force plate and the system so as to ensure an adequate volume of data acquisition.

After the application of markers subjects were asked to walk along the walkway at their usual gait speed. They were not informed of the presence of the force plates situated in the central area of the walkway to ensure that they would walk as naturally as possible. They were asked to walk until a point marked on the walkway located at approx. 1 m from its end.

After collecting reliable kinetic and kinematic data on barefoot walking, two series of cork (Table 1) heel lifts (1 cm and 2 cm high, respectively) (Fig. 2) were sequentially applied.

The study group had average height, BMI, as well as little differences in shoesize (shoesize 39; 38–41; European), which allowed us to use the same standard lift in all the subjects.

By doing so the study wanted to evaluate a chinesiological condition that would not be invalidated by possible confusing variables obtained by the use of footwear.

The data acquisition session was closed after a minimum of 5 valid tests were completed for each foot and for each situation tested (no lift, 1-cm lift and 2-cm lift) (Fig. 3).

The data collected were then used to compare the following parameters:

- Plate force data.
- Ankle joint moments, to understand whether the use of heel lifts lead to load transfer (load shift towards the forefoot).
- Knee moments, to identify possible changes caused by heel lifts (decrease in extension moment during the initial stance phase or increase in flexion moment during terminal stance and toe-off).

2.4. Statistical technique

The Wilcoxon two-tailed matched-pairs test was used to assess the significance of data comparisons ($p<0.05$).

3. Results and comments

3.1. Comparison between conditions with no heel lift vs. 2 cm heel lift: plate forces (N)

The curves of plate forces related to the lower limb of subjects walking without heel lift (L0) and with 2 cm heel lift (L2) were compared. The observations made were the following: the difference between the minimum values of the L0 curve (median $-94.27$) and the L2 curve (median $-92.04$) was highly statistically significant ($p=0.0031$); the difference between the maximum values of the L0 curve (median 128.21) and the L2 curve (median 125.92) was highly statistically significant ($p=0.0040$) (Figs. 4–6).

Similarly, the difference between maximum and minimum values (curve amplitude) was highly statistically significant (L0 median 228.91—L2 median 211.31) ($p=0.0001$).

The use of a 2-cm heel lift implies a general decrease in plate forces curve amplitude, with significantly lower
minimum values (decrease in energy absorption) and maximum values (energy generated required for push-off).

In addition, load transfer velocity was calculated on the basis of the time elapsing (distance covered) between minimum and maximum values with no heel lift (median 502.32) and with heel lift (median 455.79); the decrease in time values observed with L2 was not statistically significant ($p = 0.3757$).

The descriptive analysis of the force curve suggested that although there was no significant time difference there could be a different modality of load transfer with greater involvement of the forefoot shown by an earlier curve inversion.

The difference in curve inversion points in the L0 condition (median 0.47) and L2 condition (median 0.46) was not statistically significant ($p = 0.1909$) although it seemed that the curve inversion point tended to occur somewhat earlier during walking with heel lifts.

### 3.2. Comparison between conditions with no heel lift vs. 2 cm heel lift: ankle moments (N m/kg)

Maximum L0 values (median 1.30) and L2 values (median 1.40) were extrapolated from the ankle moments curve and compared.

The difference was not statistically significant ($p = 0.1272$).

However, in the L2 condition the ankle dorsiflexion moment tended to be greater throughout the stance phase.

The minimum values of ankle moments were not taken into account as they were virtually the same in the L0 and L2 conditions.

### 3.3. Comparison between conditions with no heel lift vs. 2 cm heel lift: knee moments (N m/kg)

The difference between the maximum values representing the extension moment in the L0 condition (median 0.49) and the L2 condition (median 0.45) measured on the knee moment curve was not statistically significant.

Conversely, a statistically significant difference was found between the minimum values of the flexion moment in the L0 condition (median $-0.46$) and the L2 condition (median $-0.53$) on the same curve ($p = 0.0494$) (Figs. 7 and 8).
Therefore, the main impact of heel lift on gait dynamics affects the knee, not so much by reducing the extension moment during the initial stance phase of the gait cycle but by increasing the flexion moment during mid-stance and heel off.

3.4. Comparison between conditions with no heel lift vs. 1 cm heel lift

For the sake of completeness the data drawn from this comparison have been included, although the initial assessment had virtually ruled out any impact of a 1-cm heel lift on gait cycle dynamics.

In fact, force plate data differences in minimum values \((p = 0.6257)\), maximum values \((p = 0.0580)\) and time values \((p = 0.3223)\) were not statistically significant.

Similarly, no statistically significant difference was found comparing maximum values of ankle moments \((p = 0.1677)\) and knee moments \((p = 0.1040)\).

4. Discussion

Although the sample investigated was rather small, the study showed that heel lifts of at least 2 cm cause significant changes in gait dynamics.

In particular, the data provided by the analysis of the force plate curve showed a statistically significant change in some parameters (plate forces, knee moments) which were deemed useful in the analysis of load transfer modalities during weight acceptance (0–15% of the gait cycle) and early weight bearing (15–40% of the gait cycle).

A very significant decrease \((p = 0.0001)\) was found in the amplitude of the curve expressing the force produced by the whole limb in response to ground reaction forces. This is expressed by a decrease in minimum values, suggesting a lower degree of energy absorption at heel strike, as well as maximum values reflecting the amount of energy generated at push off.

This might suggest that by reducing energy absorption by the whole limb a 2-cm heel lift would have a protective effect for those muscles that are most significantly involved in this function, such as the tibiotalar complex (triceps surae) and the knee complex (rectus femoris).

In the same two phases of the gait cycle the decrease in the knee extension moment was not statistically significant \((p = 0.6257)\); this was investigated on the basis of literature data suggesting that this mechanism might become involved to adjust for the increased plantar flexion induced by the heel lift. This further corroborates the hypothesis that the use of orthoses of this height would have no repercussions on the knee energy absorption mechanisms and might therefore be a useful solution.

Based on the hypothesis that the heel lift could increase load transfer velocity, we compared the duration of the periods between heel strike and toe off (distance walked). Although this value was constantly lower during walking with heel lifts the difference was not statistically significant.

In addition, the force curve also showed an earlier inversion point indicating that when walking with heel lifts there is an earlier shift from weight acceptance to heel off.

In line with the hypothesis made by Speksnijder for the use of higher heels (Speksnijder CM, 2005) this may suggest that there is an earlier involvement of the midtarsal joint and therefore of the whole forefoot in weight bearing.

However, although data were highly suggestive of this, they were not statistically significant\(^2\). In the analysis of the ankle and knee districts, more significantly involved in load absorption, the study of the ankle joint moments did not show significant differences between the various stages of the gait cycle although the use of heel lifts increases the dorsiflexion moment at terminal stance.

Conversely, and quite unexpectedly, the increase in knee flexion moment during terminal stance and heel off was statistically significant \((p = 0.0494)\).

One possible explanation might be that during mid-stance and single limb stance the subject would have an increased anterior imbalance requiring compensation through a down-shift of the barycentre and an increase in the flexion moment.

This may suggest to assess the possible increase in muscle activity with eccentric contraction of the triceps surae fibres needed to control the forward shift of the barycentre.

Another possible explanation of the increased flexion moment might be found in the research by Winter DA (1995) \([11]\) on the determinants of walking function. This suggests that the increase in knee flexion moment may result from adjustment and control mechanisms aimed at reducing the vertical shift of the mass center which is known to imply an increase in energy dispersion.

5. Conclusions

This preliminary investigation raised new questions concerning both the kinematics of the pelvis and the trunk which require further in depth-analysis and the new type of muscular activity required also by the use of low-height heel lifts.

In particular it would be useful to investigate how the system recovers the little amount of potential energy produced during the initial loading response phase and whether this could result in an increased activity of the muscles controlling both the tibiotalar and the knee joint levels.

Conflict of interest

None declared.

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\(^2\) Probably comparison of data from a larger sample (at least twice as many subjects) might have resulted in a \(p\)-value close to 5%.
References


