Forces Acting in the Forefoot During Normal Gait – A Clinical Application

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BIOMECHANICS OF THE FOREFOOT

Thesis presented for the Degree of Doctor of Philosophy

by

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Vol. I
Jacob, H.A.C:

Forces acting in the forefoot during normal gait – an estimate

Clinical Biomechanics 16 (2001) 783 – 792
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Forces acting in the forefoot during normal gait – an estimate

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• static model of the 1st and 2nd ray
Jacob, H.A.C:

Forces acting in the forefoot during normal gait – an estimate

Clinical Biomechanics 16 (2001) 783 – 792

• static model of the 1st and 2nd ray
• only guilty for the push off
External forces, determined with dynamic pressure measurement, do not correspond to the forces which really act on the foot.

Forces in % of body weight:
- $F_1 = 24$
- $F_2 = 29$
- $F_{nl} = 52$
- $F_{hb} = 36$
- $F_{pl} = 58$
- $R = 119$
External forces, determined with dynamic pressure measurement, do not correspond to the forces which really act on the foot

Forces in % of body weight:

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Forces in % of body weight:
\[ F_1 = 24 \quad F_2 = 29 \]
\[ F_{hil} = 52 \quad F_{hb} = 36 \quad F_{pl} = 58 \quad R = 119 \]
Free Body Diagram for the IP Joint of the 1st Ray
Free Body Diagram for the IP Joint of the 1st Ray

Conditions of equilibrium in the IP joint:

1) \( F_{ba} \times K_1 = F_i \times D_i \implies F_{ba} = \frac{F_i \times D_i}{K_1} \)

2) \( R_1 = F_{ba} + F_i \)

Thus leading to:

3) \( R_1 = \sqrt{F_{ba}^2 + F_i^2} \)

4) \( \theta_i = \arccos \left( \frac{F_{ba}}{R_1} \right) \)
Free Body Diagram for the MP Joint of the 1st Ray
Free Body Diagram for the MP Joint of the 1st Ray

Conditions of equilibrium at the MP joint:

5) \( F_0 \cdot K_3 + F_2 \cdot K_3 = F_1 \cdot (D_1 + D_2) \) \( \Rightarrow F_0 = \frac{F_1 \cdot (D_1 + D_2) - F_2 \cdot K_3}{K_3} \)

6) \( R_2 = F_1 + F_6 + F_3 \)
   \( R_{2x} = (F_6 + F_3) \cdot \cos \alpha_2 \)
   \( R_{2y} = F_3 - (F_6 + F_3) \cdot \sin \alpha_2 \)

Thus leading to:

7) \( R_2 = \sqrt{R_{2x}^2 + R_{2y}^2} \)

8) \( \alpha_2 = \arccos \left( \frac{R_{2x}}{R_2} \right) \)
Free Body Diagram for the MP Joint of the 1st Ray

Conditions of equilibrium at the MP joint:

5) \[ F_b \times K_3 + F_a \times K_2 = F_t \times (D_1 + D_2) \Rightarrow H_b = \frac{F_t \times (D_1 + D_2) - F_a \times K_3}{K_3} \]

6) \[ R_2 = F_t + F_{ab} + F_{fa} \]
   \[ R_{ab} = (F_{ab} + F_{fa}) \times \cos \alpha_2 \]
   \[ R_{fa} = F_t - (F_{ab} + F_{fa}) \times \sin \alpha_2 \]

Thus leading to:

7) \[ R_2 = \sqrt{R_{ab}^2 + R_{fa}^2} \]

8) \[ \theta_2 = \arccos \left( \frac{R_{fa}}{R_2} \right) \]
Clinical Application in the Daily Routine

Free Body Diagram of the TMT1 Joint
Clinical Application in the Daily Routine

Free Body Diagram of the TMT1 Joint
Clinical Application in the Daily Routine

Free Body Diagram of the TMT1 Joint
Correction of the Projection Error

\[ x + y = \text{measured length} \]
\[ \gamma = 20^\circ \]
\[ \beta = \text{measured angle} \]
\[ \alpha = 90^\circ - \beta \]
Correction of the Projection Error

\[ x + y = \text{measured length} \]
\[ \gamma = 20^\circ \]
\[ \beta = \text{measured angle} \]
\[ \alpha = 90^\circ - \beta \]

\[ M_1 = \frac{x + y}{\cos \alpha \times (\tan \alpha + \tan \gamma)} \]
Clinical Application in the Daily Routine
Clinical Application in the Daily Routine
Clinical Application in the Daily Routine
3D Motion Analysis
3D Motion Analysis

- Vicon 250 (50Hz)
3D Motion Analysis

- Vicon 250 (50Hz)
- 5 Cameras
3D Motion Analysis

- Vicon 250 (50Hz)
- 5 Cameras
- unilateral
Clinical Application in the Daily Routine
Clinical Application in the Daily Routine
Methods

Dynamic pressure measurement
Methods

Dynamic pressure measurement

• 4 Sensors per square cm
Methods

Dynamic pressure measurement

- 4 Sensors per square cm
- 50 Hz
Methods

Dynamic pressure measurement

- 4 Sensors per square cm
- 50 Hz
- Second step method, 5 trials
Methods

Dynamic pressure measurement

- 4 Sensors per square cm
- 50 Hz
- Second step method, 5 trials
- Gait velocity chosen freely
Dynamic Pressure Measurement

- Standardised mask with 12 areas
Dynamic Pressure Measurement

- Standardised mask with 12 areas
- Forces were normalized to the body weight. Body weight = 100%
Dynamic Pressure Measurement

- Standardised mask with 12 areas
- Forces were normalized to the body weight. Body weight = 100%
- Time normalization
  > Each step is divided into 100 intervals
Dynamic Pressure Measurement

- Standardised mask with 12 areas
- Forces were normalized to the body weight. Body weight = 100%
- Time normalization
  > Each step is divided into 100 intervals
  > Linear interpolation
Dynamic Pressure Measurement

- Standardised mask with 12 areas
- Forces were normalized to the body weight. Body weight = 100%
- Time normalization
  - Each step is divided into 100 intervals
  - Linear interpolation
- 5 trials > in each interval > Median/StDv
Muscle Forces

Inverse Dynamics
Muscle Forces

Inverse Dynamics using EMG

\[
F_{\text{hl}} = \frac{F_2 \cdot M_1' + F_1 \cdot (D_1 + D_2 + M_1') - F_{\text{hl}} \cdot K_2 - F_{\text{hb}} \cdot K_4}{K_6}
\]

\[
F_{\text{hl}} = \frac{F_1 \cdot D_1}{K_4}
\]

\[
F_{\text{hb}} = \frac{F_1 \cdot (D_1 + D_2) + F_{\text{hl}} \cdot K_2}{K_3}
\]
Muscle Forces

Inverse Dynamics using EMG
Clinical Approach

- 5 Trials
- Median
- Standard Deviation
Clinical Approach

- 5 Trials
- Median
- Standard Deviation

more than 2 standard deviations >> pathologically
Clinical Approach

- 5 Trials
- Median
- Standard Deviation

more than 2 standard deviations >> pathologically
Clinical Example: Metatarsalgia, conservatively treated without success

Case 1

Distal Hallux Valgus Surgery

Case 2

Distal Hallux Valgus Surgery + Weil-Osteotomy
Gait Analysis Data: Increased Total Force on MTH 2

Case 1

Case 2

Total Force on MTH 2

Aim of the computer simulation:

to decrease patients data (blue line) to the norm
Computer simulated treatment with Insoles
Decrease of 40% of the external force
Computer simulated treatment with Insoles

Decrease of 40% of the external force

Case 1

Total Force on MTH 2

Insole = useful
Computer simulated treatment with Insoles
Decrease of 40% of the external force

Case 1
Insole = useful

Case 2
Insole not useful
Computer simulated treatment with PIP arthrodesis

Shortening of the Phalanx of 1cm
Computer simulated treatment with PIP arthrodesis
Shortening of the Phalanx of 1cm

Case 1

Total Force on MTH 2

PIP resection not useful
Computer simulated treatment with PIP arthrodesis

Shortening of the Phalanx of 1cm

Case 1

Case 2

Total Force on MTH 2

Stance Phase

Total Force on MTH 2

Stance Phase

PIP resection not useful

PIP resection probably useful
Computer simulated treatment with tenotomy of FDL
Computer simulated treatment with tenotomy of FDL

Case 1

Total Force on MTH 2

Tenotomy not useful
Computer simulated treatment with tenotomy of FDL

Case 1

Case 2

Total Force on MTH 2

Total Force on MTH 2

Stance Phase

Stance Phase

Tenotomy not useful

Tenotomy excellent
Computer simulated treatment with shortening of MT 2

Decrease of 40%, shortening of the metatarsal of 1cm
Computer simulated treatment with shortening of MT 2
Decrease of 40%, shortening of the metatarsal of 1cm

Case 1

Osteotomy could be useful
not better than the insole
Computer simulated treatment with shortening of MT 2

Decrease of 40%, shortening of the metatarsal of 1cm

Case 1

Total Force on MTH 2

Stance Phase

Osteotomy could be useful
not better than the insole

Case 2

Total Force on MTH 2

Stance Phase

Osteotomy not useful
Shortening of the second metatarsal leads not to a significant reduced total force on the metatarsal head.
1. Is there a correlation between the length of the metatarsals and increased forces at the metatarsal heads
Theoretical Study
Theoretical Study

Determination of the Intraarticular Force
Theoretical Study

Determination of the Resultant Force
Experimental Study

Finite Element Method
(Space Truss Elements)

<table>
<thead>
<tr>
<th>element</th>
<th>node i</th>
<th>node j</th>
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<tbody>
<tr>
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<td>2</td>
</tr>
<tr>
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<td>3</td>
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<tr>
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</tbody>
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13 element model
X ray to get the coordinates of the elements
X ray to get the coordinates of the elements
AMTI 3 D Force Plate
AMTI 3 D Force Plate + EMED SF
Pressure measurement
Pattern of abnormal tangential forces in the diabetic neuropathic foot

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X ray to get the coordinates of the elements
Shortening of 1 cm of the metatarsal 2 leads to an increased force in the vertical direction of 4%
Shortening of 1 cm of the metatarsal 2 leads to an increased force in the vertical direction of 4%

~ 1% Body Weight (stdv = 7% BW)
The change of the resultant force at the second metatarsal head after a shortening is not significant and is not due to the shortening itself.
It is due to the reduced force at the tip of the second toe because of loosening of toe function after the operation
Experimental Study

50 healthy / 50 metatarsalgia
Experimental Study

50 healthy / 50 metatarsalgia

No correlation between length of metatarsals and the resultant or intraarticular forces
2. Is there a correlation between metatarsalgia and increased forces at the metatarsal heads
Healthy (n=505) versus Metatarsalgia (n=342)

<table>
<thead>
<tr>
<th>Ray</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Pressure</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
<td><img src="image5.png" alt="Graph" /></td>
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<tr>
<td>External Force</td>
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<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
<td><img src="image9.png" alt="Graph" /></td>
<td><img src="image10.png" alt="Graph" /></td>
</tr>
<tr>
<td>Intraart. Force</td>
<td><img src="image11.png" alt="Graph" /></td>
<td><img src="image12.png" alt="Graph" /></td>
<td><img src="image13.png" alt="Graph" /></td>
<td><img src="image14.png" alt="Graph" /></td>
<td><img src="image15.png" alt="Graph" /></td>
</tr>
<tr>
<td>Resultant Force</td>
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<td><img src="image19.png" alt="Graph" /></td>
<td><img src="image20.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

- **Significant decrease**
- **Significant increase**
The Facts

- The resultant forces at the metatarsal heads do not correlate with the external forces
The Facts

• The resultant forces at the metatarsal heads do not correlate with the external forces
• The resultant forces are higher than external forces
The Facts

• The resultant forces at the metatarsal heads do not correlate with the external forces

• The resultant forces are higher than external forces

• Metatarsalgia correlates not with increased resultant forces
The Facts

• The resultant forces at the metatarsal heads do not correlate with the external forces

• The resultant forces are higher than external forces

• Metatarsalgia correlates not with increased resultant forces

• The length of metatarsals correlates not with increased forces
In Conclusion

We should not believe in orthopedic surgeons' doctrin we should measure the problem.
Kantonsspital Aarau

Department of Orthopedic Foot Surgery
Gait Laboratory

Thank you for your attention