12-31-2006

Analysis of the Characteristics of Pressure-time Curve under Peak Metatarsal Plantar Pressure Site of Healthy Adults

Jiunn-Horng Kang
Shih-Ching Chen
Jin-Shin Lai
Wei-Li Hsi

Follow this and additional works at: https://rps.researchcommons.org/journal

Part of the Rehabilitation and Therapy Commons

Recommended Citation
Kang, Jiunn-Horng; Chen, Shih-Ching; Lai, Jin-Shin; and Hsi, Wei-Li (2006) "Analysis of the Characteristics of Pressure-time Curve under Peak Metatarsal Plantar Pressure Site of Healthy Adults," Rehabilitation Practice and Science: Vol. 34: Iss. 4, Article 2.
DOI: 10.6315/2006.34(4)02
Available at: https://rps.researchcommons.org/journal/vol34/iss4/2

This Original Article is brought to you for free and open access by Rehabilitation Practice and Science. It has been accepted for inclusion in Rehabilitation Practice and Science by an authorized editor of Rehabilitation Practice and Science. For more information, please contact twpmrscore@gmail.com.
Analysis of the Characteristics of Pressure-time Curve under Peak Metatarsal Plantar Pressure Site of Healthy Adults

Jiunn-Horng Kang, Shih-Ching Chen, Jin-Shin Lai, Wei-Li Hsi

Department of Physical Medicine and Rehabilitation, Taipei Medical University Hospital, Taipei; Department of Physical Medicine and Rehabilitation, National Taiwan University Hospital, Taipei.

The purpose of this study was to describe the characteristics of the pressure-time curve under the peak metatarsal pressure site during walking. Plantar pressures were measured at the forefoot area of 30 healthy adults during walking using high resolution transducers with the first step method. The pressure data at each time frame under the peak metatarsal pressure site were extracted and analyzed. A mathemetic model was calculated to approximate this curve with the least square residual. The patterns of pressure-time curves under the peak metatarsal pressure sites were very similar in all subjects. After forefoot contact, it was an increasing curve which had two different components with different slopes. The approximate model of the pressure-time curve with least square residual at peak pressure site was the cubic equation which can be expressed as \( P(t) = \alpha t^3 + \beta t^2 + \gamma t + \delta \). The means of coefficients of approximate function \( \alpha \) was 13491±8214, \( \beta \) was -9005±5643, \( \gamma \) was 2414±1496, and \( \delta \) was 2400±1102 (the unit of \( P(t) \) is kPa, and \( t \) is second). The correlations between weight, height and each coefficient (\( \alpha \), \( \beta \), and \( \gamma \)) were statistically insignificant. Further study in the correlation between pathological conditions and changes of the pressure-time curves should be conducted. (Tw J Phys Med Rehabil 2006; 34(4): 209 - 214)

Key words: metatarsal bones, plantar pressure, pressure-time curve

INTRODUCTION

The plantar pressure measurements have been applied in several clinical proposes. The measurements aid the diagnosis, treatment, prediction of outcome, and follow up in a variety of foot pathologies.\(^{1-5}\)

Several parameters obtained using plantar pressure measurements such as peak pressure, contact time, pressure-time integrals, and ground reaction force have been studied under normal and pathological conditions.\(^{6-8}\) Researchers have reported that the maximal plantar pressure frequently occurred under the second metatarsal head.\(^{3,9,10}\) However, to our knowledge, the metatarsal plantar pressure-time curve during the phase from forefoot contact to terminal push-off is still not well described.
The plantar pressure under the metatarsal head is higher than other components of the normal foot and it changes very rapidly during walking. The metatarsal plantar pressure is determined by the complex biomechanical interaction such as muscle strength, metatarsal-pharyngeal (MP) joint mobility, anatomical features of feet and plantar soft tissue biomaterial parameters.\textsuperscript{[6,7,10]} The goal of this study was to describe the temporal pattern of the metatarsal plantar pressure during walking and establish an approximate mathematical model of pressure-time curve for clinical application.

**METHODS**

Our study included 30 healthy adults (15 women and 15 men) without congenital or traumatic deformities of the lower extremities, history of foot pain, or traumatic injuries to the ankles or feet 12 months prior to the data collection. Their ages, height and weight are listed in Table 1. The experimental protocol was selected as a modified first step method as in our previous study.\textsuperscript{[11]}

We followed the human experimental procedures standards set forth by our institutional review board. Before the tests began, all subjects signed the informed consent forms. Plantar pressure measurements were taken from a randomly assigned barefoot using the Pliance 16P (Novel GmbH, Munich, Germany), which contains 256 pressure sensors of 2.54 mm x 2.54 mm in each with a sampling rate of 38 Hz. The modified first step method was used as following. Before data collection, the subjects were asked to walk in their ordinary speed along a 12-m long walkway. After excluding the first two steps and the last four steps, the length covered by all the sequential steps was measured and divided by the number of steps for average step length. Tape marks were placed on one average step length behind and one average step length in front of the pad. Each subject stood with his assigned foot just behind the pad and the other foot on the first mark. After two practice sessions, each subject was instructed to start walking forward by stepping the forefoot of his assigned foot onto the pad from a stationary heel-contact posture, then the other foot onto the second mark, and continued to walk along for four more steps.

The highest peak pressure sensor among the trials was identified first, and each time frame in this sensor was analyzed. The data were plotted as a curve of pressure versus time and analyzed by statistic software. A mathematical model was calculated with least square residual to approximate the origin curve using S-plus software (Insightful Corporation, Seattle, Wash USA). Student’s $t$ test was selected to compare peak plantar pressure data and coefficients between the male and female subjects. The Pearson correlation test was used for analysis of the correlation between coefficients, weight, and height to determine statistical significance. Significance level was set at $p<0.05$.

**RESULTS**

The mean peak plantar pressure under metatarsal heads of 30 healthy adults was 792 kPa (range, 400 to 1400 kPa; standard deviation, 226 kPa) (Table 2). The plantar pressure plotted as a function of time under the peak metatarsal plantar site was a simple increasing function. The patterns of pressure-time curves under peak metatarsal pressure sites were very similar in all subjects. Two major components were identified using the different increasing slopes: the first component, phase I, was a concave-up increasing component which was reaching a plateau, and the second component, phase II, was also a concave-up curve which increased more rapidly than in phase I (Figure. 1). The mathematical model with least residual calculated using S-plus was a cubic equation which was expressed as $P(t)=\alpha t^3+\beta t^2+\gamma t+\delta$ (the unit of $P(t)$ was kPa, and $t$ was second). The mean and standard deviation of each coefficient were $13491\pm8214$ (range, 3437 to 28785) for $\alpha$, $-9005\pm5643$ (range, $-2745$ to $-22415$) for $\beta$, $2414\pm1496$ (range, 1067 to 5430) for $\gamma$, and $2440\pm1102$ (range, 1305 to 3865) for $\delta$. Comparison the coefficients of approximate mathematic equations between the female and male subjects were performed, and the differences of coefficients between genders were not significant (Table 3). The Pearson’s correlation between each coefficient and weight, and height were statistically not significant (Table 4).

**DISCUSSION**

The normal human gait pattern is highly habitual in development with normal temporal and spatial parameters. The gait cycle can be divided into the stance and swing
Pressure-time Curve under the Metatarsal Head

211

phases during functional analysis. The typical plantar pressure recordings in the stance phase have two peak values at two different sites, the heel and metatarsal head, which correspond to two main biomechanical tasks: shock absorption and push-off.[12,13] It has been reported that the maximal plantar pressure frequently occurred under the second metatarsal head due to small contact area and active muscle contraction to push-off.[7,13-16] It is reasonable to deduce that temporal progression pattern of plantar pressure at the metatarsal head would be a characteristic reflecting the biomechanical process in healthy adults. We found that the pattern of pressure-time curve at the peak metatarsal pressure site was similar in all subjects, and the pressure-time curve could be divided into two distinct phases. These findings may be explained by a specific biomechanical interaction during the heel-rising to toe-off. The first phase was from the forefoot contact to loading response just before the heel rise. Biomechanical features during this phase advance the body mass by contra-lateral limb swing. Passive lengthening of calf muscle and dorsiflexion of ankle also occur during this phase. This phase of pressure-time curve increased less rapidly and achieved a plateau in our study corresponding to gradually shifting center of gravity from the hindfoot to the forefoot. The second phase was from heel rise to push-off. Several muscle groups activate including calf muscles, flexor digitorum muscles, flexor hallucis muscles, and intrinsic muscles to provide further power for body advancing and stabilize the foot structure complex. This biomechanical interaction can explain why the plantar pressure in this phase increased more rapidly than first phase. When we correlated the current study of multi-segmented foot kinematics with our data, we found that the plantar pressure-time curve highly correlated with the MP joint kinematics data from a previously published report.[12] While the foot-flat initiated during the stance phase, the plantar pressure started to rise slowly while the MP joint angle was nearly unchanged. While MP joints were extended during late stance, the plantar pressure increased more rapidly than during previous phases until the peak value was reach. It is reasonable to propose that the MP joint mobility highly correlate with the temporal pattern of the plantar pressure, especially during the second phase in our study.

Table 1.  Age, weight, and height of subjects

<table>
<thead>
<tr>
<th></th>
<th>Age (year)</th>
<th>Body weight (kg)*</th>
<th>Body height (cm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>24.9±3.1</td>
<td>72.1±7.0</td>
<td>174.1±5.7</td>
</tr>
<tr>
<td>Female</td>
<td>24.7±3.2</td>
<td>52.7±6.6</td>
<td>161.4±6.6</td>
</tr>
<tr>
<td>All</td>
<td>24.8±3.1</td>
<td>62.4±11.9</td>
<td>167.8±8.9</td>
</tr>
</tbody>
</table>

* Significant at p < 0.05.

Table 2.  Peak pressure under metatarsal head of all subjects

<table>
<thead>
<tr>
<th></th>
<th>Peak pressure (mean±SD) (kPa)</th>
<th>Range (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Female</td>
<td>758±195</td>
<td>430-1130</td>
</tr>
<tr>
<td>Male</td>
<td>826±325</td>
<td>400-1400</td>
</tr>
<tr>
<td>All</td>
<td>792±226</td>
<td>400-1400</td>
</tr>
</tbody>
</table>

*No statistical significant between males and females at p<0.05

Table 3.  Coefficients of approximate cubic model of pressure-time curve

<table>
<thead>
<tr>
<th></th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean±SD</td>
<td>Range</td>
<td>Mean±SD</td>
<td>Range</td>
</tr>
<tr>
<td>Female (n=15)</td>
<td>11977±7905</td>
<td>3437-27710</td>
<td>-8836±5950</td>
</tr>
<tr>
<td>Male (n=15)</td>
<td>13097±7765</td>
<td>4400-28785</td>
<td>-8421±4382</td>
</tr>
<tr>
<td>All (n=30)</td>
<td>13491±8214</td>
<td>3437-28785</td>
<td>-9005±5643</td>
</tr>
<tr>
<td>p –value</td>
<td>0.698</td>
<td>0.829</td>
<td>0.873</td>
</tr>
</tbody>
</table>
Table 4. Pearson’s correlation between each coefficient of approximate cubic model and body weight and body height

<table>
<thead>
<tr>
<th>Correlation</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body Weight</td>
<td>-0.023</td>
<td>0.09</td>
<td>0.03</td>
</tr>
<tr>
<td>Body Height</td>
<td>-0.089</td>
<td>0.09</td>
<td>-0.24</td>
</tr>
</tbody>
</table>

No correlation was significant at p < 0.05.

The pressure-time curve can be interfered with by many factors due to the complex biomechanical process during this period. It is reasonable to assume that this curve could be characteristic in many different pathological conditions such as diabetic foot, ankle or foot contracture, after operation of foot or ankle, and foot deformity, etc. Further comparisons using different clinical conditions to the normal patterns presented in our study can help us to understand the relationship between the pathological conditions and biomechanical changes. It is also possible to detect the early changes of subtle biomechanical deviation in patients with pathological conditions or evaluate the prognosis by analysis the pressure-time curve at the peak metatarsal pressure site.

It is possible to identify the changes of the pressure-time curve by direct visualization, but it is too subjective for clinical use. In contrast, transforming the curve to a mathematic model and analyzing the coefficients of the mathematic model could be easier for clinical application. There are many possible mathematic models to approximate pressure-time curve at the peak metatarsal pressure site. We calculated linear, quadratic, and cubic mathematic models to approximate this curve using S-plus, and we found the cubic model was the best to approximate mathematic model of pressure-time curve with the least square residual. This finding may reflect the fact that the metatarsal plantar pressure increased very rapidly just after the MP joint began to extend at the terminal stance.

There are still some insufficiencies in our study such as protocol variance and poor velocity control. There were many test protocols for plantar pressure measurement in the present studies. However, each plantar pressure measurement protocol has its limitation. Barefoot first step protocol may increase the value of the forefoot plantar pressure, and terminal stance protocol may increase at the heel plantar pressure, etc. We used the Pliance-16 system for better resolution with good reliability. However, the size of the measurement area was too small to use the mid-stance or terminal stance protocol due to technical difficulties. As previous studies showed, the parameters of plantar pressure were relative to the walking velocity and protocols. The data from our study may only be applied in the same circumstances for clinical appliance. Further study should be conducted using insole devices at different walking velocities to study the inference of the walking velocity to the pres-
pressure-time curve under peak metatarsal pressure site. High variability of coefficients of our model was noted, and may have resulted in difficulties in clinical interpretation. In addition, the high variability of the coefficients may cause high beta error when the Pearson’s correlation between coefficients and weight, height, and gender were statistically insignificant. This observation may reflect the fact that the variability of the metatarsal pressure and forefoot contact time were high in normal individuals.

The pressure-time curve of the peak plantar pressure under the metatarsal head was highly relative to the locomotion biomechanics. Our study established norm data of peak metatarsal pressure-time curve of normal adults using a mathematic model to approximate this curve. Further studies should be conducted using several dimensions such as comparing the normal data of plantar pressure-time curve of the different measurement protocols and the changes of pressure-time curve patterns in pathological conditions such as metatarsalgia, diabetic foot, etc.

ACKNOWLEDGEMENTS

This study was supported by a research grant from the National Science Council, Taiwan, ROC (NSC91-2314-B-002-357).

REFERENCES

正常人踵骨尖峰壓力區之壓力時間曲線分析

康峻宏  陳適卿  賴金鑫  施偉立

台北醫學大學附設醫院復健科  國立臺灣大學醫學院附設醫院復健部

足底壓力測量是研究足部問題的良好工具，能對臨床處埋足部病變提供進一步關於診斷、治療及預後的資訊。本研究主要在分析正常行走下，尖峰踵骨壓力區下的壓力—時間變化曲線。

本研究總計測量30名未有足部問題的健康成年人，男性及女性各15人，平均年齡為24.8歲。採用第一步方式，利用高解析度的壓力感測鞋墊量測前足區之壓力變化。分析前足區之壓力，針對踵骨區最高峰值壓力區進行時間變化的分析，並對於壓力—時間變化曲線建立最小平方殘差的近似曲線。我們發現所有受試者的壓力—時間曲線型態上都十分相似，曲線為一漸增曲線並可觀察到有兩種不同斜率的上升部份。最小平方殘差之近似曲線為三次方曲線：

\[ P(t) = \alpha \times t^3 + \beta \times t^2 + \gamma \times t + \delta, \]

四個係數的平均值(範圍)依次為: 13491±8214 (3437 to 28785), -9005±5643 (-2745 to -22415), 2414±1496 (1067 to 5430), 2400±1102 (1305 to 3865) (P(t) 單位為 kPa, t 的單位為秒)。各項係數與體重、身高、統計上的相關性並不明顯。

我們認為，行走時在尖峰踵骨壓力區下的壓力—時間曲線具有一定的特徵，本研究提供健康年輕人行走時踵骨壓力峰峰值的壓力—時間曲線近似曲線的係數常模值，分析曲線型態的變化及近似曲線的性質可能是進一步評估足部疾病的工具。（台灣復健醫誌 2006; 34(4): 209 - 214）

關鍵詞：踵骨(Metatarsal bones), 足底壓力(plantar pressure), 壓力—時間曲線(pressure-time curve)