Biomechanics of Hip, Knee and Ankle joint loading during ascent and descent walking

Ahmad Nisam Amirudin\textsuperscript{a}, S.Parasuraman\textsuperscript{b,*}, Amudha Kadirvel\textsuperscript{b} M.K.A Ahmed Khan\textsuperscript{c}, I.Elamvazuthi\textsuperscript{d}

\textsuperscript{a,b}School of Engineering, Monash University Malaysia, Bandar Sunway, 46150 Selangor, Malaysia.  
\textsuperscript{c}Faculty of Engineering, University Selangor, Malaysia.  
\textsuperscript{d}Faculty of Engineering, University Technology Petronas, Ipoh, Malaysia.

Abstract

A comprehensive movement analysis of stair climbing can support the evaluation of gait rehabilitation, joint replacement or prostheses development. In addition to this, the analysis of biomechanical and motor control aspects involved in staircase ascent and descent can be useful in the design of private and public environment where staircase is employed. This research study provides the investigations of biomechanics and motor coordination in human’s lower extremity during ascent and descent walking at different inclinations. Five normal subjects were ascended and descended a 3 step staircase at various inclinations. Subject’s footsteps were instrumented with force sensors and provided footstep ground reaction force components at Metatarsals and Heel. Kinematics of Hip, Ankle and Knee was analyzed using Human Motion Tracking System and the results were discussed. Joint moments and force were computed using Inverse kinematics. A large impact on aging verses inclinations were observed in Hip, Knee and Ankle joint movements and discussed in the results session.

Keywords: Biomechanics, Kinematics, Lower extremity, Motor control, Rehabilitation.

Nomenclature

\(a_x, a_y\) = Acceleration of segment COM  
\(\theta\) = Angle of segment in plane of movement  
\(\alpha\) = angular acceleration of segment in plane of movement  
\(R_{xd}, R_{yd}\) = reaction forces acting at distal end of segment, obtained from pressure insole  
\(M_d\) = net muscle moment acting at distal joint  
\(R_{xp}, R_{yp}\) = reaction forces acting at proximal joint  
\(M_p\) = net muscle moment acting on segment at proximal joint

* Corresponding author. Tel.: +603 55146254; fax: +60355146207.  
E-mail address: s.parasuraman@monash.edu
1. Introduction

Several studies were performed to investigate normal human stair ascent and descent [1,2]. The analysis of joint moments [3], joint power [4], plantar pressure characteristics [5] and reproducibility [6] during staircase walking provides good evidences for the assessment of over loading effects and further rehabilitation treatments. Other investigations such as staircase climbing of patients with knee [7] and hip [8], implants amputees with artificial limb [9, 10] supports the evaluation of joint replacement or prosthetics developments. However, no comprehensive analyses are available in literature that discusses biomechanics of ascent and descent at different inclinations by considering ground reaction force, affecting kinematics gait parameters at hip, knee and ankle. The pressure distribution under the foot or the ground reaction forces are generally propagated to ankle, knee and hip. Although these have been extensively used in biomechanics of footwear [10] they have been received little attention in the clinical application area such as ankle, knee and hip rehabilitation. In this paper, methods to compute the ground reaction force and the related kinematics and force propagations at all lower extremity are discussed.

2. Methods

A stair case was developed that allowed the collection of kinetic and kinematics data for multiple steps at various inclination. Five subjects are taken into consideration with an age of 23.6±3.0496 years; height, 172±5.1478m; mass, 71±6.2048kg; BMI, 24±1.9777 to collect the moment exerted at joint loadings around the knee and ankle. Among the subjects selected, one has a flat back syndrome but the condition would not affect the walking pattern drastically. TABLE I shows that the subject has a mean height of 172cm and a mean weight of 23.6kg. There are two techniques which are proposed such as surface markers and pressure insole techniques to measure the relevant kinematics data, which are being used in the computing the force and torques propagation at ankle and knee. Surface markers are round retro-reflective balls which are placed on the anatomical points of the lower extremities of the subject in order to capture its motion using Motion capturing system when carrying out the task of ascending and descending staircase. This data would return the position, velocity and acceleration of each of the marker balls. With this, the joint forces can be calculated and moment obtained as each of the variables would have a x,y and z components.

Table-1 Subject’s profile

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Gender</th>
<th>Age (Years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>BMI</th>
<th>Status</th>
<th>Medical History</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject 1</td>
<td>Male</td>
<td>22</td>
<td>176</td>
<td>68</td>
<td>21.95</td>
<td>Desirable</td>
<td>Healthy</td>
</tr>
<tr>
<td>Subject 2</td>
<td>Male</td>
<td>23</td>
<td>169</td>
<td>63</td>
<td>22.06</td>
<td>Desirable</td>
<td>Healthy</td>
</tr>
<tr>
<td>Subject 3</td>
<td>Male</td>
<td>22</td>
<td>168</td>
<td>70</td>
<td>24.8</td>
<td>Desirable</td>
<td>Flat Back Syndrome</td>
</tr>
<tr>
<td>Subject 4</td>
<td>Male</td>
<td>22</td>
<td>168</td>
<td>75</td>
<td>26.57</td>
<td>Slightly Overweight</td>
<td>Healthy</td>
</tr>
<tr>
<td>Subject 5</td>
<td>Male</td>
<td>29</td>
<td>179</td>
<td>79</td>
<td>24.66</td>
<td>Desirable</td>
<td>Healthy</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>23.6</td>
<td>172</td>
<td>71</td>
<td>24</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>-</td>
<td>3.0495</td>
<td>5.1478</td>
<td>6.2048</td>
<td>1.9777</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The markers are placed in the lower extremities from the hip downwards. The red dots represent markers which would be used to define each segment, the green dots are for tracking and the blue dots are only for segment definitions. The surface markers are used in order to obtain the kinematics data through the usage of 6 Oqus Cameras which are placed strategically at 6 locations around the roof to obtain the best reading. The surface markers are made out of a special scotch-lite reflective film which lets the camera identify the markers easily. The markers are placed with according to c-motion’s marker set guidelines as can be seen in Figure 1(a), which shows the marker placement around the thigh segment and the picture on the right hand side indicates the placement for the shank. The motion captured by Oqus cameras are then interfaced with Qualisys Track Manager. It is able to capture up to 1000 frames per sec and in order to capture the marker coordination perfectly, the frame rate are set to 247 frames per second. All six Oqus cameras are calibrated for the experimental work envelop and shown in Figure 1(c).
Hydrocell pressure insole is a microchip which is embedded inside a fluid like casing called discrete piezoresistance sensors where it would return a voltage parameter when the planter sole takes a step and pressure is applied upon. With the known voltage and pressure relationship, the force is then able to be calculated to carry out the force and torque propagation. This fluid filled cell is then placed at three locations below a flexible insole as can be seen in Figure 1 (b). It is placed at the first metatarsal, fifth metatarsal and also at the heel of the foot in order to capture the voltage induced when walking up the stairs that will be used to calculate the force. The insole used on each of the individual varies to suit the size of the subject’s foot. This hydrocell is then interface with an acquisition board which is equipped with an amplifier that would amplify the output up to 462mV with a zero pressure offset of 20mV. The data acquisition of the hydrocell pressure insole are obtained using DI-148U analogue to digital converter by DATAQ instruments. The signal is sampled at the frequency of 90Hz.

![Image](image1.png)

**Figure 1.** (a) Marker Placement on the thigh and shank (b) placement of Hydro cell (c ) Oqus cameras calibration

### 3. Results and Discussions

From the specification of the sheet, the area of the hydro cell pressure insole (349 mm²) and sensitivity of 0.58 mV/kPa are obtained to compute the subject’s foot pressure and force. In Figure 2, the linear envelope waveform is superimposed onto each other to be able to view the stepping motion of subject 2. By inspecting the waveform, there is a clear two-peaked when a footstep is taken where the first is a resultant from the heel strike whereas the second peak is from the toe push off. The first section of the two-peak in Figure which is between 1.5 seconds to 3 seconds have a much higher reading than the second section of peak which is between 3.5 seconds to 4.5 seconds is because more effort is required when taking a step on the staircase. The two sections show the two levels of steps that the foot has travelled on. In order to calculate the pressure and ultimately the ground reaction force applied by the subject, the peak of each hydrocell in the first section at heel, first

![Image](image2.png)

**Figure 2.** Superposition of the three hydrocell readings in order to identify stepping pattern
Metatarsal and fifth metatarsals are 151.4, 191.3 and 166.4 mV respectively. Since the pressure is the ratio between the peak data and sensitivity, the pressure and the corresponding force of each point heel, first metatarsal and fifth metatarsal) are computed and shown in Figures 3(a) to 3(d).

Figure 3 (a) Schematic representation of limb postures during two flights of stairs, Force applied by foot when (b) ascending (c) descending staircase by subject 2, (d) Ascending by Subject 3.

From the results obtained, this shows that from the heels strike to toe off, mainly the force is concentrated at the first metatarsal area on the plantar foot. This is true for subject 2 and the other subjects experimented besides subject 3 where the walking pattern is different and can be seen in Figure 3 c that the force is much greater at the fifth metatarsal area instead at the first metatarsal area. This may be due to the medical history of flat back condition carried by the subject into the experiment. The same results of all subjects are presented in Tables 2.
Figure 3 shows the collective results for all the muscles cascaded on top of each other to clearly show the differences between them. In the starting position of the experiment, the subject stood upright with their feet parallel to each other and spaced out comfortably with arms akimbo. In the mid stance, the foot would be flat on the ground and the weight of the body would be directly over the supporting limb where in this case it would be the right leg. The whole gait cycle would then start again with the heel rise of the right foot in order to reach the second step of the staircase. This activates the calf muscle in order to enable the body to push up and move on to the next step.

It can be concluded from the tables that when ascending and descending staircase, the main part of the foot which takes the most force would be at the first metatarsal. There is very little correlation, which can be made with the weight of the subject, and the force they exert as each individual would have a unique walking pattern therefore the forces may vary. While ascending, subject 1 showed the highest amount of force in all three hydrocell pressure readings with a value of 123.8N, 100N and 121.1N on the heel, first metatarsal and fifth metatarsal respectively. When descending, the force at the first metatarsal is great for all of the subjects and there is a pattern in the amount of force recorded and the subject’s weight.

### 3.1. Joint Moments and Forces on Subjects

**Gravitational Forces:** This is the force of gravity which is acting in the downward direction through the segment’s center of mass (COM) and is equal to the acceleration due to gravity which is approximately 9.8 m/s².

**Ground Reaction Force:** These forces are obtained from the pressure insole previously where the forces are distributed under the area of the foot. In this experiment, it is considered that it acts at a point either at the heel or at the first metatarsal.

**Joint Reaction Forces:** The link segment model is broken down into its segmental parts and the free body diagram is shown in Figure 4. Each of the segments would act independently under the influence of reaction forces and muscle moments.

Follow this order when typing manuscripts:

(1) [Forces and Moments]

(2) [Disscusion on Results]

<table>
<thead>
<tr>
<th>Subject</th>
<th>Weight</th>
<th>Heel (N)</th>
<th>1st Metatarsal (N)</th>
<th>5th Metatarsal (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68</td>
<td>123.8</td>
<td>100</td>
<td>121.1</td>
</tr>
<tr>
<td>2</td>
<td>63</td>
<td>91.07</td>
<td>115.1</td>
<td>100.1</td>
</tr>
<tr>
<td>3</td>
<td>70</td>
<td>89.1</td>
<td>87.85</td>
<td>111.1</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>90.1</td>
<td>175</td>
<td>71.6</td>
</tr>
<tr>
<td>5</td>
<td>79</td>
<td>110</td>
<td>102</td>
<td>84.1</td>
</tr>
<tr>
<td>Average</td>
<td>71</td>
<td>100.794</td>
<td>108.916</td>
<td>96.346</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>6.2048</td>
<td>15.5052</td>
<td>38.0461</td>
<td>19.9965</td>
</tr>
</tbody>
</table>
The horizontal and vertical forces as well as the moment around the ankle and knee were computed using the leg link segments of the free body diagram and the models (1) and (2). For the subject which are analyzed, the mass of the subject is 63kg and the mass of the foot is given by 0.0145 M which equals to 0.0145 * 63 = 0.9135 Kg. The reaction force at distal end is obtained from pressure insole readings which were computed earlier. There is a negative sign in the to indicate that the force acting on the foot at the ankle joint is in the downward direction.

\[ (4) \]
\[ (5) \]
\[ (6) \]
\[ (7) \]

There is a negative sign to indicate that the force acting on the foot at the ankle joint is in the downward direction. Therefore to calculate the moment around the ankle

\[ (8) \]
\[ (9) \]

The negative sign once again indicates the real direction of the muscle moment which is acting clockwise at the ankle joint. In order to calculate the muscle moment at the foot, it is approximated that the ankle-metatarsal length is 20cm and the inertial characteristics of the foot are calculated using the anthropometrics data [11]. The static point is taken at time 3.8seconds as shown in Figure 5(a) and (b).
From Eqn (8)

\begin{equation}
(10)
\end{equation}

Based on the above equations, the moments and forces are computed and tabulated as in Tables 4. It can be analysed from the data that when the BMI of a subject is higher, the loading at the joints is much greater than a lower BMI subject. The highest BMI is subject 4 with a BMI of 26.57 and the moment calculated is 1.388Nm. Though it is not the highest among the subjects but just slightly lower than subject 5. This may be due to the fact that subject 5 weights 9kg more than subject 4 therefore a higher moment is required to cause the horizontal acceleration of the foot’s centre of gravity to angularly accelerate the low moment of inertia of the foot. The moments at the ankle are all positive therefore indicating that the ankle is undergoing plantar flexion where it is at toe off. The forces in the x and y plane for the knee joints ranges between 4.46N to 9.208N and 30.703N to 90.8834N respectively.
Table 4. Forces at joints in the horizontal and vertical and the joint moments

<table>
<thead>
<tr>
<th>Subject</th>
<th>BMI</th>
<th>Ankle Rx2 (N)</th>
<th>Ankle Ry2 (N)</th>
<th>Ankle M2 (Nm)</th>
<th>Knee Rx1 (N)</th>
<th>Knee Ry1 (N)</th>
<th>Knee M1 (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.95</td>
<td>8.00757</td>
<td>15.2189</td>
<td>1.24916</td>
<td>7.94871</td>
<td>47.5626</td>
<td>-3.8169</td>
</tr>
<tr>
<td>2</td>
<td>22.06</td>
<td>4.6095</td>
<td>7.14</td>
<td>0.7569</td>
<td>4.4762</td>
<td>30.703</td>
<td>-1.444</td>
</tr>
<tr>
<td>3</td>
<td>24.8</td>
<td>5.73314</td>
<td>15.7652</td>
<td>1.03579</td>
<td>5.70111</td>
<td>70.8911</td>
<td>-8.1183</td>
</tr>
<tr>
<td>4</td>
<td>26.57</td>
<td>8.96667</td>
<td>17.3953</td>
<td>1.38805</td>
<td>8.95609</td>
<td>66.5287</td>
<td>-6.4785</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>2.0483</td>
<td>4.5097</td>
<td>0.2801</td>
<td>2.0814</td>
<td>23.0185</td>
<td>3.2902</td>
</tr>
</tbody>
</table>

A consequence of the forefoot placement during stair climbing compared to the heel placement during level walking is that the ankle has to produce a higher plantar flexion moment during the initial stance phase in order to keep the heel lifted. This finding agrees with the observation that the Centre of Pressure path starts at the anterior part of the foot. The above-mentioned findings lead to the assumption that there is a certain inclination angle or angular range, where the subjects switch their gait patterns and, thus, their motor control strategy between level and stair walking. This change must occur at an inclination angle below 24° and might be related to the condition at which initial foot placement switches from heel contact to forefoot contact. Further studies are necessary to confirm this hypothesis and detect the inclination at which this switch between gait patterns takes place.

4. Conclusions

Concisely, several comparisons have been made on the human locomotion in particular the lower extremities. Hydrocell pressure insole was implemented in order to find the force on the foot with the ground. It is found that the first metatarsal would have the greatest force when ascending and descending staircase. The moments and forces on the joints of ankle and knee were calculated using the forces obtained from the hydrocell pressure insole. Subject 4 with a maximum BMI of 26.57 obtained a moment of 1.388Nm and -6.4785Nm for the knee and ankle respectively. Subject 1 with the minimum BMI of 21.95 obtained a moment of 1.2491Nm and -3.8169Nm for the knee and ankle respectively. This shows that there is a relationship between the BMI of the subject and also the respective loads at each of the joints. With the data presented, this may help to aid the studies in the field to improve the results for developing solutions for human impairments and assistive techniques for the rehabilitation of the human lower extremity.

5. References


