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Biomechanical Analysis of Human Stair Climbing (Ascending and Descending)

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ABSTRACT

Because stair climbing is a common activity of daily living, the ability to do it efficiently is important to an individual's quality of life. More demanding than level walking, stair ambulation is performed with ease by healthy individuals; however, it is more difficult to perform for those with decrements in motor function, balance problems, or reduced lower-limb function. The difficulty with stair climbing is attributable to increased muscular demands, which are reflected in larger forces, angles, powers, moments, and ranges of motion, and these increased demands occur consistently at the knee joint.

Kinematic system is used in stair climbing to record the position and orientation of the body segments, the angles of the joints and the corresponding linear and angular velocities and acceleration. The purpose of the study is to show an ideal kinematics appearance of human gait cycle for stair climbing in order to get measurement values that can be depended on in the hospitals of rehabilitation, the centers of physical therapy and the clinical of medical sports as a reference data for kinematic joint parameter. In this study, 5 subjects were selected from the society, then a video recording was made for them by using a single digital video camera recorder fitted on a stand of three legs in a sagittal plane while subjects climbing a stair one by one for different stair heights. Motion analysis was used to study the knee and hip joint kinematics.

As a result, it was observed that the range of motion at the hip joint is between (10°-70°) at ascending and the range is between (20°-50°) at descending. The range of motion at the knee joint is between (20°-90°) at ascending and the range is between (10°-100°) at descending. The range of motion at the ankle joint is between (-25°-20°) at ascending and the range is between (-25°-15°) at descending. Also it was found that the angular velocity at the hip joint is between (-10-10) deg/s for ascending and (-15-25) deg/s for descending. The angular velocity at the knee joint is between (-40-30) deg/s for ascending and (-30-50) deg/s for descending. The angular velocity at the ankle joint is between (-30-20) deg/s for ascending and (-15-15) deg/s for descending. In this study, biomechanical characteristics of lower limb joint upon various stair height were presented and these data can be applied to biomedical research field that include wearable walking assistant robot.

Keywords: kinematic analysis, stair climbing, stair height, ascent, descent.

تحليل ميكانيكي احيائي لحركة الانسان أثناء صعود السلالم ونزولها

الخلاصـــــــة

أن تسلّق السلالم من الأنشطة المعيشية اليومية، والقدرة على أدائها بكفاءة مهم بالنسبة للفرد. أن عملية صعود السلام ونزولها أصعب من عملية المشي خاصة بالنسبة الى الأشخاص الذين يعانون من مشاكل مرضية. إنّ الصعوبة في ذلك راجع الى الجهود العضلية المتزايدةِ والتي تحتاج الى قوى عالية وزوايا أكبر وطاقة أعلى خاصة في مفصل الركبة.

يستخدم التحليل الحركي لحساب زوايا المفاصل والسرع والتعجيل وبالتالي حساب القوى المتولدة. غرض الدراسة هو تحليل لدورة مثالية لصعود السلم ونزوله والتي يُمكِن الاستفادة منها في مستشفيات إعادةِ التأهيل، مراكز العلاج الطبيعي والسريريين مِنْ الألعاب الرياضيةِ الطبية. في هذه الدراسة تم تسجيل حركات لخمس أشخاص باستخدام آلة تصوير فيديو رقمية لثلاثة ارتفاعات مختلفة من السلالم. تم حساب الزوايا لمقصل الورك والركبة والكاحل.

لوحظ من النتائج أنّ مدى الحركةِ في مفصلِ الورك بين (10°-70°) في الصُعُود والمدى بين (20°-50°) في النزول. ومدى الحركة في مفصل الركبة بين (20°-90°) في الصعود والمدى بين (10°-100°) في النزول. ومدى الحركة في مفصلِ الكاحل بين (-25°-20°) في الصعود والمدى بين (-25°-15°) في النزول. كذلك وجد أن السرعة الزاوية في مفصلِ الورك بين (-10-10) درجة/ثانية للصعود و(-15-25) درجة/ثانية للنزول. والسرعة الزاوية في مفصل الركبة بين (-40-30) درجة/ثانية للصعود و(-30-50) درجة/ثانية للنزول. والسرعة الزاوية في مفصل الكاحل بين (-30-20) درجة/ثانية للصعود و(-15-15) درجة/ثانية للنزول.

INTRODUCTION

The climbing a stair is very important movement because of its relevance to the daily activities, and the cooperation of the human with the machine can be analyzed in phases where higher support from the exoskeleton can be contributed, as well as smaller forces have to be applied to allow positioning the foot over the next step [1].

The gluteus maximus is a massive, powerful muscle that is usually active only when the hip is in flexion, as during stair climbing. Compressive force at the tibiofemoral joint has been reported to be slightly greater than three times body weight during the stance phase of gait, increasing up to around four times body weight during stair climbing. Compressive force at the patellofemoral joint has been found to be one half body weight during normal walking gait, increasing up to over three times body weight during stair climbing [2].

Jonathan et al (2002) [3] evaluate weighted stair climbing exercise as a means of increasing lower extremity muscle power in mobility-limited older people. They suggest that stair climbing exercise be a useful component of a home exercise program designed to enhance lower extremity muscle power, aerobic capacity and functional performance.

Wells et al [4] studied a functional comparison of biomechanical outcomes during gait and stair climbing was carried out for younger individuals with these two alternative hip arthroplasties. They conclude that reduction in the abduction and flexion moments appear to be the most significant outcomes effecting function. Resurfaced hips may function slightly better.

Robert et al (2002) [5] investigated the biomechanics and motor co-ordination in human stair climbing at different inclinations. They suggested that there is a certain inclination angle range where subjects do switch between a level walking and a stair walking gait pattern.

Patrick et al (2002) [6] examined hip and knee joint kinetics during stair climbing in 35 young healthy subjects using a subject-specific knee model to estimate bone-on-bone tibiofemoral and patella-femoral joint contact forces. They found that the most striking difference between stair ascent and level walking was that the peak patella-femoral contact force was 8 times higher during stair ascent.

Samantha et al (2005) [7] compared the kinematics and kinetics of the knee joint during traditional step-over-step and compensatory step-by-step lead-leg and trail-leg stair ambulation patterns. They concluded that the overall step-by-step lead-leg during ascent and trail-leg during descent had the highest loads.

Samantha et al (2009) [8] used principal component analysis to compare the gait patterns between young and older adults during stair climbing. They concluded that the principal component analysis and discriminant function analysis applied in their investigation indentified gait pattern differences between young and older adults.

AIM OF THE STUDY

The purpose of the study is to show a biomechanical study for stair climbing in order to get measurement values that can be depended on in the hospitals of rehabilitation, the centers of physical therapy and the clinical of medical sports, instead of depending on the measurement values that are dependent on the development countries for the same movement. The analysis investigated the biomechanics and motor co-ordination in humans during stair climbing at different stair height.

STAIR ASCENT AND DESCENT

In stair climbing, a cycle constitutes the movement of the body from one step up or down to the next. A cycle begins with both feet on a stair and begins when one foot is lifted or pulled off the surface of the step. In stair ascent, the initial phase, termed limb lift, ends when the foot is placed securely on the next step. At this point in the cycle, pull-up begins. This phase involves the forceful extension of the limb on the next step to elevate the body from the original step. The phase ends when the foot of the limb on the original step contacts the subsequent step. In stair descent, the events are similarly named, although the actions are different Figure (1a).

Stair ascent and descent have similar patterns to those described for walking and running. However, the hip muscles generally contribute less than the muscles acting on the knee and ankle joints. A review of the muscles contributing to ascent and descent is presented in Figure (1b). Going upstairs, or ascent, is first initiated with a limb lift via vigorous contraction of the iliopsoas, which pulls the limb up against gravity to the next stair. The rectus femoris becomes active in this phase as it assists in the thigh flexion and eccentrically slows the knee flexion [2].

Next, the foot is placed on the next step. At this point, there is activity in the hamstrings, primarily working to slow down the extension at the knee joint. As the foot makes contact with the next step, weight acceptance involves some activity in the extensors of the thigh.

The next phase is pull-up, in which the limb placed on the upper step is extended to bring the body tip to that step. Most of the extension is generated at the knee joint.

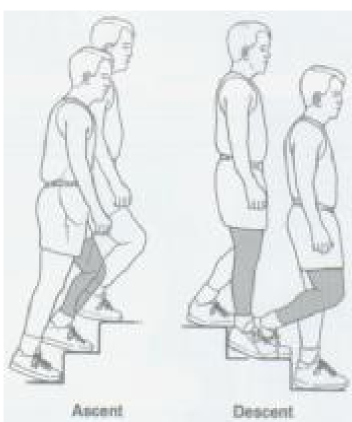
There is minimal contribution from the hip other than contraction by the gluteus medius to pull the trunk up over the limb. Finally, in the forward propelling stage in which the limb on the lower step pushes up to the next step, there is minimal activity at the hip, with the ankle joint generating the most of the force.

Going downstairs, or descent, requires minimal hip muscular activity. In the limb pull phase, the hip flexors are active, followed by hamstring activity in the foot placement phase, when the limb is lowered to the sup surface. As the limb makes contact with the next step in weight acceptance, the hip is minimally involved, as most of the weight is eccentrically absorbed at the knee and ankle joints. The muscles acting at the knee joint are primarily responsible for generating the forces in the forward propelling phase.

In the final phase of support, the controlled lowering phase, the body is lowered onto the step primarily through eccentric muscle activity at the knee joint. There is a minimum amount of hip extensor activity at the end of this phase.

In stair climbing, it is the limb on the higher step that produces the greatest effort for both ascent and descent.

The knee joint is more active in ascent than descent and the hip joint activity is small in both, being almost negligible in the descent phase.



Stair Climbing

Muscle	*Ascent*	*Descent*
Dorsiflexors		*
Gluteus Medius		**
Hamstrings		*
Iliopsoas		**
Plantar Flexors		**
Quadriceps		**

* Low activity
** Moderate activity
*** High activity

(a) (b)

Figure (1) In stair ascent with the left limb leading, there is significant contribution from the quadriceps, with assistance from the plantar flexors and the iliopsoas. In descent with the right limb leading, the same muscles control the movement eccentrically. For stair climbing as a whole, there is less contribution from the hip muscles than in walking or running. [2]

KINEMATICS OF STAIR CLIMBING

Kinematics of stair climbing involves the study of the shape, pattern, form of motion, and sequencing of movement with respect to time, without particular reference to the force or forces that cause or result from the motion. Biomechanists commonly use high-speed cinematography or videography to perform quantitative kinematic analyses. The process involves taking a carefully planned film or video of a performance, with subsequent computerized or computer-assisted analysis of the on a picture-by-picture basis.

The anatomical coordinate (x, y) of the knee joint node K:

$$x = L_1 cos\theta_1, y = L_1 sin\theta_1$$

The anatomical coordinate (x, y) of the ankle joint node A:

$$x = L_1 cos\theta_1 \pm L_2 cos\theta_2,$$
$$y = L_1 sin\theta_1 \pm L_2 sin\theta_2$$

The anatomical coordinate (x, y) of contact node C:

$$x = L_1 cos\theta_1 \pm L_2 cos\theta_2 \pm L_3 cos\theta_3,$$
$$y = L_1 sin\theta_1 \pm L_2 sin\theta_2 \pm L_3 sin\theta_3$$

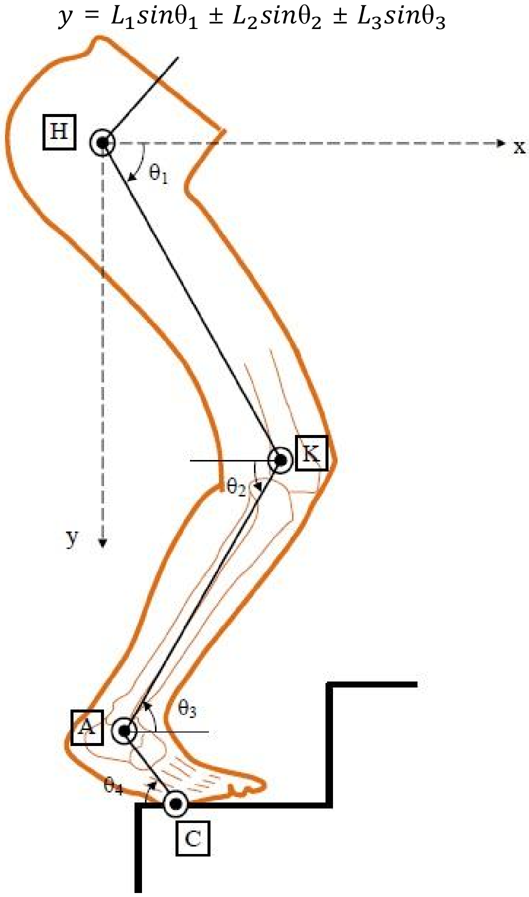


Figure (2) Four link planar analysis of saggital plane stair climbing

KINETICS OF STAIR CLIMBING

Kinetics of stair climbing is the study of the forces associated with this motion. Human movement involves simultaneous tension development in agonist and antagonist muscle groups. The tension in the antagonists controls the velocity of the movement and enhances the stability of the joint at which the movement is occurring. Since antagonist tension development creates torque in the direction opposite that of the torque produced by the agonist, the resulting movement at the joint is a function of the net torque [1].

Figure (3) shows a free body diagram of the knee joint. To analyze the internal and external forces it is necessary to know the force line of action and point of application of muscles within the musculoskeletal structure. For this reason, kinesiological data is of importance in biomechanical modeling as well as anthropometric and mechanical capacity data.

The three main coplanar forces acting on the lower leg: ground reaction force (F_g), patellar tendon force (F_p), and joint reaction force (F_J) are designed on a free body diagram of the lower leg while climbing stairs. Because the lower leg is in equilibrium, the lines of application for all three forces intersect at one point. Because the lines of application for two forces (F_g and F_p) are know the line of application for the third force (F_J) can be determined. The line of application for forces F_g and F_p are extended until they intersect. The line of application for J can then be drown from its point of application to the tibial surface through the intersection point.

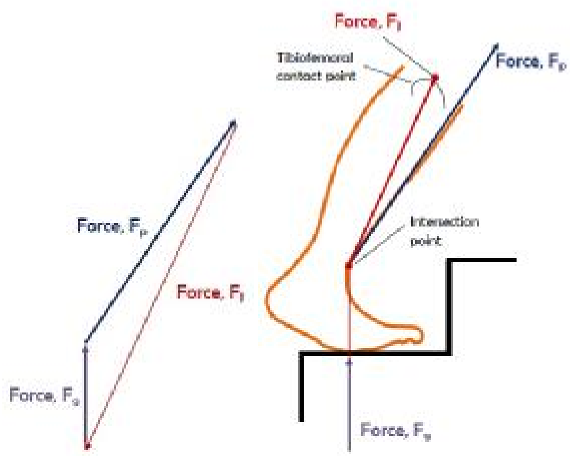


Figure (3) Free body diagram of the lower leg during stair climbing

The two main moments acting around the center of motion of the tibiofemoral joint are designed on the free body diagram of the lower leg during stair climbing.

The flexing moment on the lower leg is the product of the weight of the body (F_g, the ground reaction force) and its lever arm (a), which is the perpendicular distance of the force F_g to the center of motion of the tibiofemoral joint. The counterbalancing extending moment is the product of the quadriceps muscle force through the patellar tendon (F_p) and its lever arm (b). Because the lower leg is in equilibrium, the sum of these two moments must equal zero ($\sum M = 0$).

The counterclockwise moment is arbitrarily designed as possible ($F_g \times a = F_p \times b = 0$). Values for lever arms a and b can be measured from anatomical specimens or on soft tissue imaging or fluoroscopy, and the magnitude of F_g can be determined from the body weight of the individual. The magnitude of F_p can then be found from the moment equilibrium equation:

$$F_p = \frac{F_g \times a}{b}$$

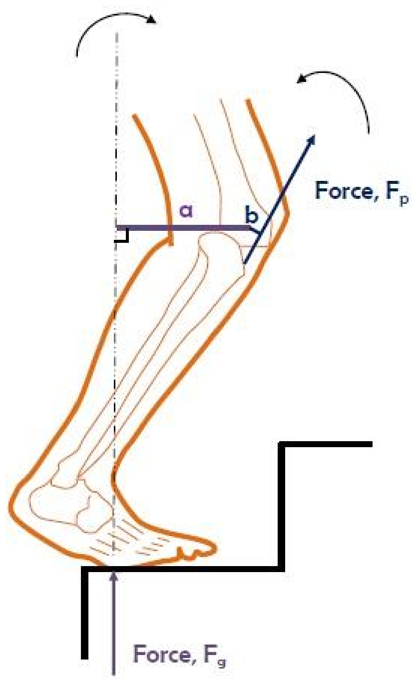


Figure (4) Two main moments diagram of the lower leg during stair climbing

MATERIALS AND METHODS

Two-dimensional motion was obtained by using a single digital video camera recorder, this camera gives 25 frames per second, it contains video compression format [MPEG2/JPEG] (still images), recording time [approximately 650 minute]. Have a hard disk [30 giga byte], Handy cam station and USB cable to transport the recording videos from the hard disk by connecting it to the computer. The camera is fitted on a stand of three legs then located perpendicular to the line of progression as subjects walked, the camera is fitted at high (1) m and the distance of the camera from the center of the trajectory line of the subject is (2.80) m.

A sufficiently high frame rate will ensure that the instances of maximum and minimum displacement (linear and angular) of a joint or limb, and of other key events in a performance are recorded. An increase in the frame rate will also serve to improve the precision, and therefore the accuracy, of temporal measurements, for example, the phase durations of a movement. This is particularly important where the phases are of short duration. For stair climbing, 25-50 Hz frame was suggested by Carl et al [9].

Three different stair heights (15, 20, 25cm) are used in this analysis to show the effect on joint angles and joint reaction forces, Fig.(5) and (6).

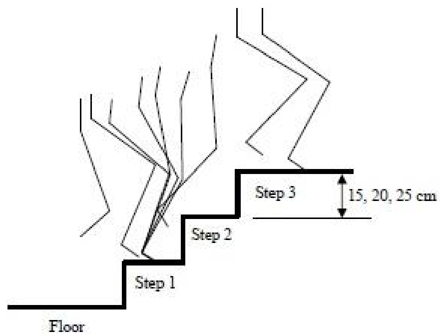


Figure (5) Movement of hip, knee, and ankle during ascending

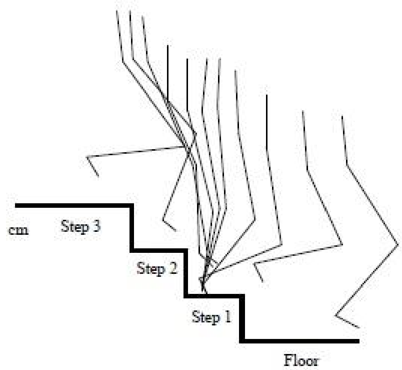


Figure (6) Movement of hip, knee, and ankle during descending

The hip, knee, and ankle angles from complete cycle for five volunteers at three different stair heights (15, 20, 25 cm) were measured as shown in (Figs.7-10) as examples for both ascending and descending.

Selecting normal subject to get for it the absolute angular changes at hip, knee, and ankle joints from three complete cycles, by using the software to get the diagram of stick figures that represent the angular changes at that joints, to calculate the angular velocity at the hip, knee and ankle joints then the measurement absolute angle divided by the time. The angular velocities at the hip, knee, and ankle joints are divided by the time at each step to calculate the angular acceleration. Mat lab program is used to show a graphical representation of its hip, knee, and ankle angular velocities and angular accelerations.

Figure (7) Stair climbing (ascent), stair height = 20 cm

Figure (8) Stair climbing (descent) stair height = 20 cm

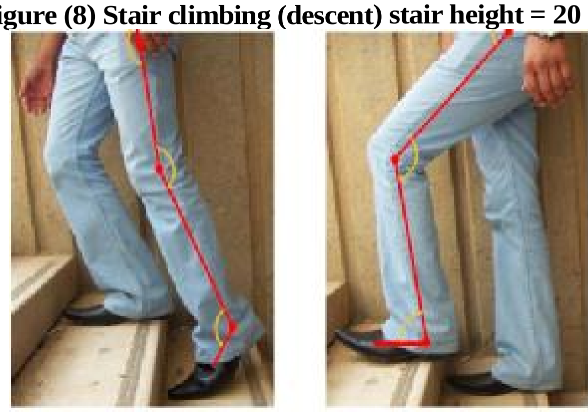


Figure (9) Stair climbing (ascent), stair height = 15 cm

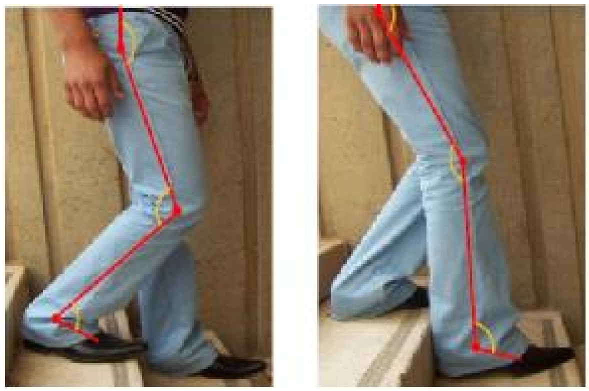


Figure (10) Stair climbing (descent) stair height = 15 cm

RESULTS AND DISCUSSION

From the graphical representation of one normal subject at the hip there is a single peak of flexion at descent and two at ascent in each cycle. In ascent, the hip flexes during the stance phase, and then starts to decrease flexion until reaches a minimum value at about 60% of gait cycle. The range of hip flexion is about 55 degrees (Fig.11). In descent, the hip flexes and then starts to increase flexion until reaches a maximum value at about 75% of gait cycle. The range of hip flexion is about 25 degrees (Fig.12).

From the graphical representation of the subject at the knee one peaks of flexion for ascent and descent. In ascent, the knee flexes during the stance phase, and then starts to decrease flexion until reaches a minimum value at about 50% of gait cycle, then increases to reach a peak value at about 65% of gait cycle, then decreases again at the end of gait cycle. The range of knee flexion is about 80 degrees (Figs.13). In descent, the knee flexes and then starts to increase flexion until reaches a maximum value at about 66% of gait cycle, then decreases at about 80% of gait cycle. The range of knee flexion is about 90 degrees (Fig.14).

From the graphical representation of the subject at the ankle three peaks of flexion for ascent and descent. In ascent, the ankle flexes during the stance phase, and then starts to decrease flexion until reaches a minimum value at about 30% of gait cycle, then increases to reach a peak value at about 65% of gait cycle, then decreases again at the end of gait cycle. The range of ankle flexion is about 45 degrees (Fig.15). In descent, the ankle flexes and then starts to increase flexion until reaches a maximum value at about 68% of gait cycle, then decreases at the end of gait cycle. The range of ankle flexion is about 40 degrees (Fig.16).

Figs.(11) to Fig.(16) show that increase the stair height will increase both the hip, knee and ankle joint angles, and the decrease of stair height will decrease them.

Considerable differences were also observed when comparing joint angles during stair ascent and descent, which is in agreement with previous studies [7].

Results for hip joint angular velocity are shown in Fig.(17) for ascending and Fig.(18) for descending. Results for knee joint angular velocity (change in joint angle per time) are shown in Fig.(19) for ascending and Fig.(20) for descending. Results for ankle joint angular velocity are shown in Fig.(21) for ascending and Fig.(22) for descending.

Fig.(23) to Fig.(28) show the angular acceleration (change in joint angular velocity per time) for hip, knee, and ankle for both ascending and descending.
Results for joint reaction forces are shown in Fig.(29) for ascent and Fig.(30) for descent. Two peaks are shown for both ascent and descent. Maximum joint reaction force is 350N at about 85% of gait cycle for ascent, and 370N at about 20% of gait cycle for descent.

CONCLUSIONS

1. Hip, knee and ankle angles differ in each gait cycle of stair climbing, similarly to spatial-temporal parameters (step, stride length and the stride rate), the primary independent variables is the variability of step length, step width, and step time.
2. The effect of stair height on the joint reaction forces increases for both ascent and descent stair climbing for different stair height, which increase joint moments.
3. Considerable differences were also observed when comparing joint angles, velocity, acceleration, and reaction forces during stair ascent and descent, which is an agreement with previous studies.

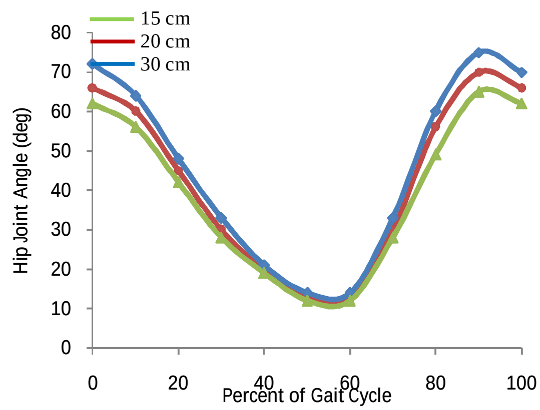


Figure (11) Hip joint angles during ascent at different step levels

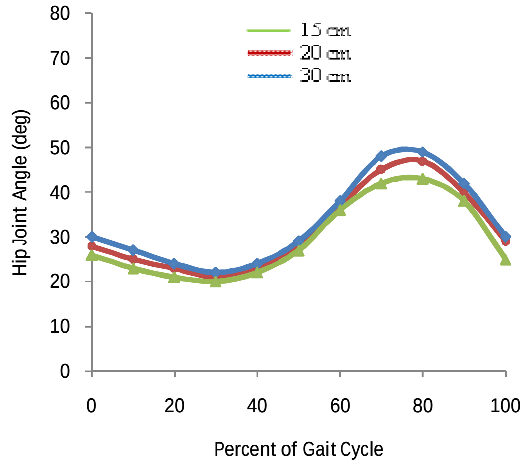


Figure (12) Hip joint angles during descent at different step levels

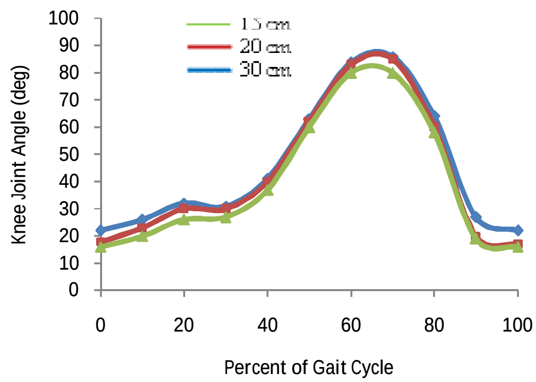


Figure (13) Knee joint angles during ascent at different step levels

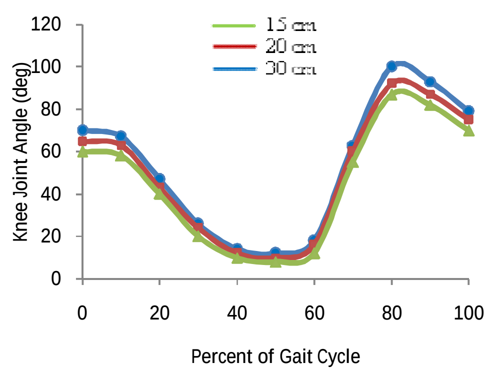


Figure (14) Knee joint angles during descent at different step levels

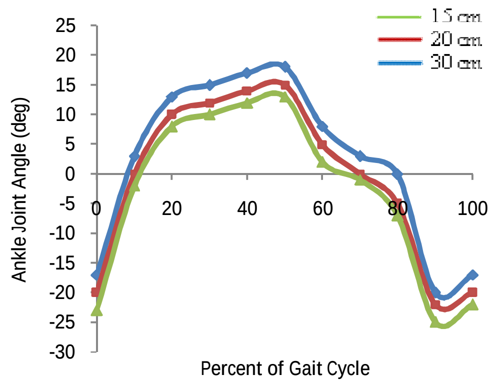


Figure (15) Ankle joint angles during ascent at different step levels

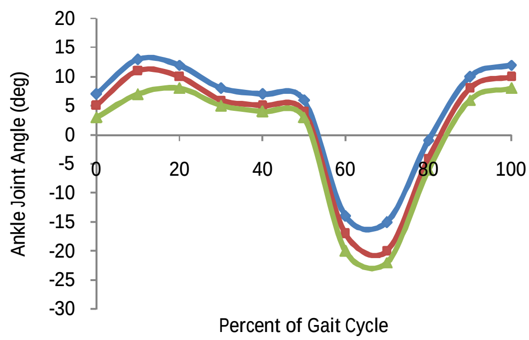


Figure (16) Ankle joint angles during descent at different step levels

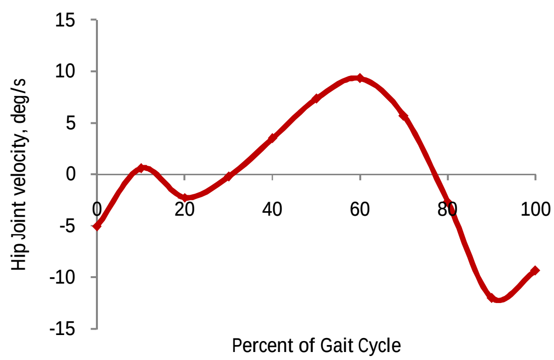


Figure (17) Hip joint velocity during ascent

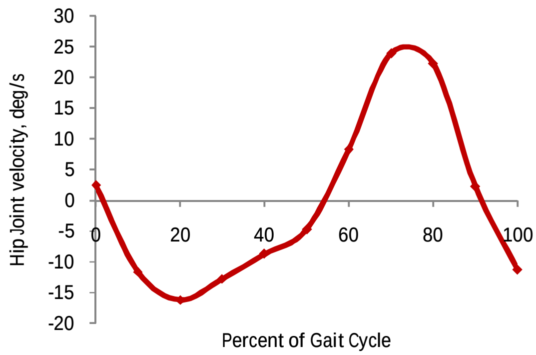


Figure (18) Hip joint velocity during descent

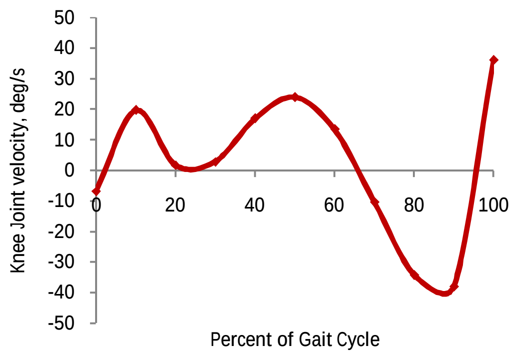


Figure (19) Knee joint velocity during ascent

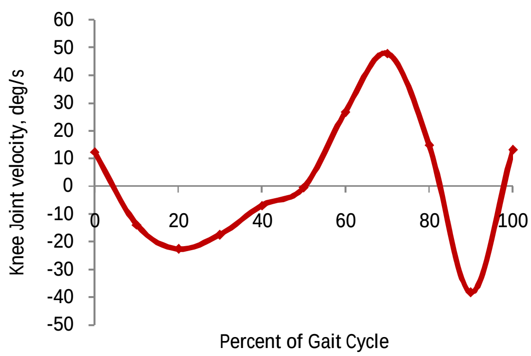


Figure (20) Knee joint velocity during descent

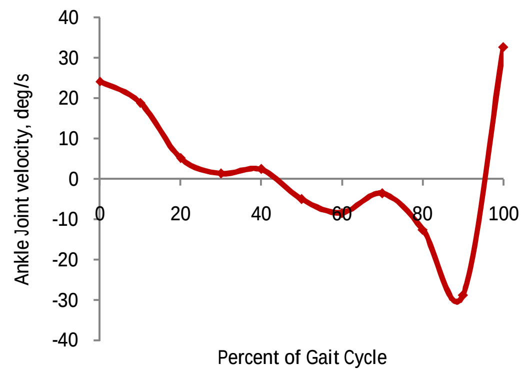


Figure (21) Ankle joint velocity during ascent

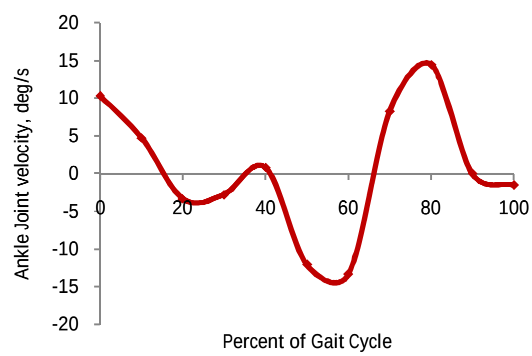


Figure (22) Ankle joint velocity during descent

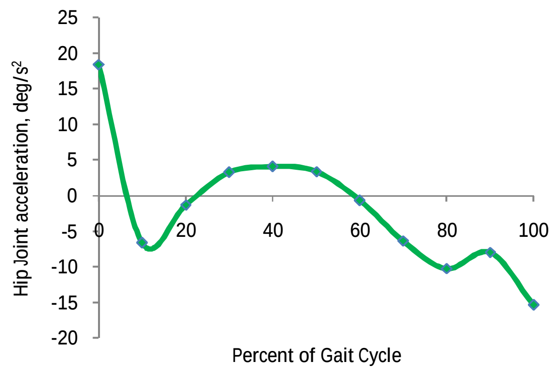


Figure (23) Hip joint acceleration during ascent

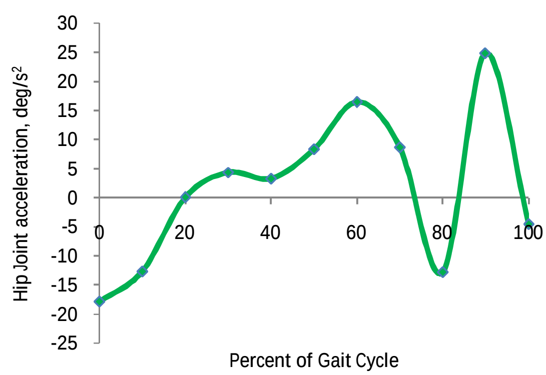


Figure (24) Hip joint acceleration during descent

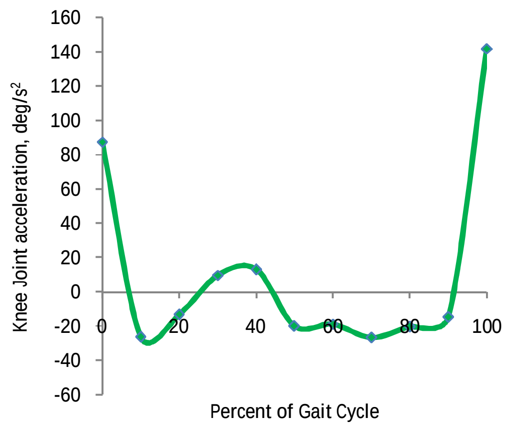


Figure (25) Knee joint acceleration during ascent

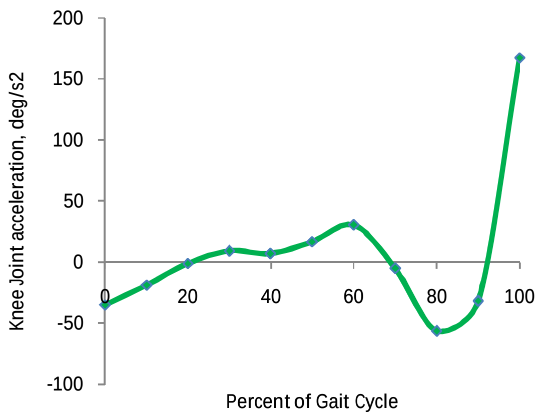


Figure (26) Knee joint acceleration during descent

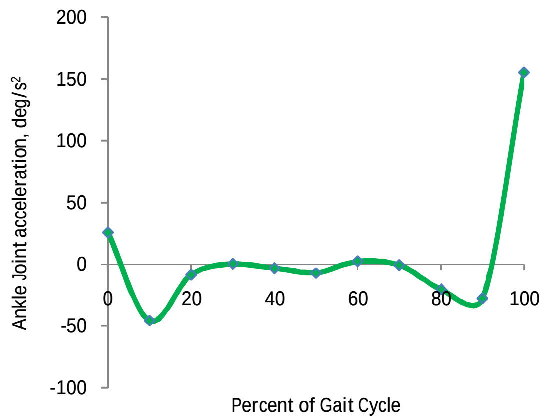


Figure (27) Ankle joint acceleration during ascent

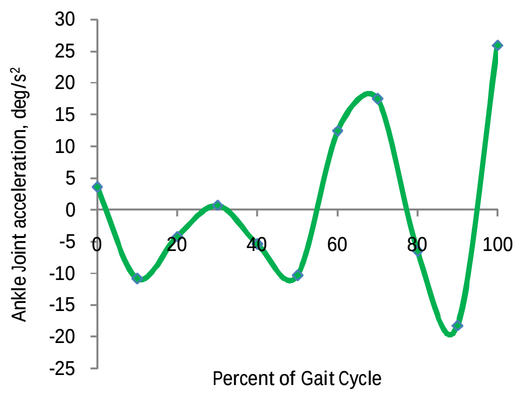


Figure (28) Ankle joint acceleration during descent

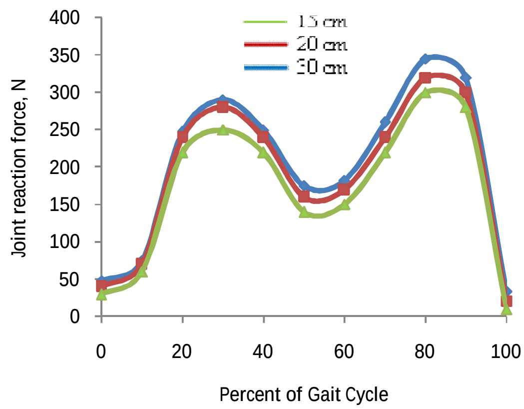


Figure (29) Joint Reaction force during ascent at different step levels

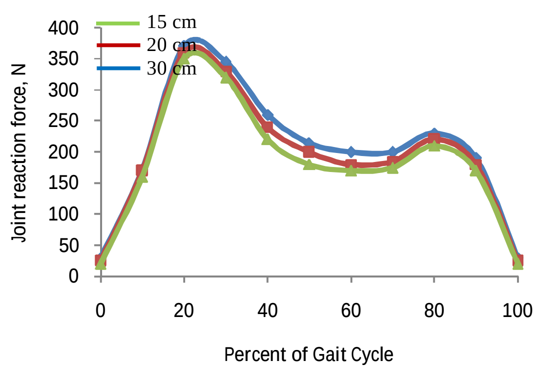


Figure (30) Joint Reaction force during descent at different step levels

REFERENCES

[1]Susan J. Hall, 1995, "Basic Biomechanics", The McGraw-Hill Companies, Inc.

[2]McFadyen, B. J., Winter, D. A. (1988). An integrated biomechanical analysis of normal stair ascent and descent. Journal of Biomechanics, 21: 733-744.

[3]Jonathan, B., Seth H., Dan, K., Damien, C., Kelly, M., Walter R., Roger A., "Weighted stair climbing in mobility-limited older people: A pilot study", JAGS S0:663-670, 2002, American Geriatrics Society.

[4] Wells, J. A. A.C. Nicol, R. Ingram and A. Stark. "Functional joint biomechanics following stemmed or resurfacing hip arthroplasty",

[5]Bioengineering

[6]Unit, University of Strathclyde, Glasgow, UK.

[7]Robert Riener, Marco Rabuffettim, and Carlo Frigo. "Stair ascent and decent at different inclinations". Elsevier Science B.V. Gait and Posture 15 (2002) 32-44.

[8]Patrick A. Costigan, Kevin J. Deluzio, Urs P. Wyss. "Knee and hip kinetics during normal stair climbing". Elsevier Science B.V. Gait and Posture 16 (2002) 31-37.

[9]Samantha M. Reid, Scott K. Lynn, Reilly P. Musselman, and Patrick A. Costigan. "Knee biomechanics of alternate stair ambulation patterns". Official Journal of the American College of Sports Medicine, 2007.

[10]Samantha M. Reid, Ryan B. Graham, and Patrick A. Costigan. "Differentiation of young and older adult stair climbing gait using principal component analysis. Gait Posture (2009).

[11]Carl J. Payton and Roger M. Bartlett, "BIOMECHANICAL EVALUATION OF MOVEMENT IN SPORT AND EXERCISE", 2008 by Routledge.