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Analysis of Stair Climbing to Find an Optimum Knee Angle in Order to Reduce the Chances of Leg Muscle Fatigue and Injuries

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Abstract- **Stair climbing is one of the unique exercises which is frequently used and helps in maintaining the leg muscles active and healthy. However, if the height of the stair is not optimum, it may cause serious injuries due to increased or decreased knee angle that may damage the human leg muscles such as quadriceps and hamstring involved in its proper function. A stair climbing leg model PASCO ME-7001 was designed to find an optimum knee angle for reducing the maximum chances of leg muscle fatigue and injuries by using the force sensors. Resultant forces applied on leg muscles i.e. hamstring and quadriceps at 4 different average angles: 40º, 57º, 68º, and 76º for four different stair heights: 3", 5", 7", and 9" respectively were studied graphically during ascending stairs. Also, the energy consumption of quadriceps is calculated for the desired 4 average angles. The optimum knee angle maybe 57-68 degrees at 5"-7" stair height for both flexion and extension of the leg during stair climbing.**

Index Terms-- **Leg muscle fatigue/injuries, optimum knee angle, optimum stair height, stair climbing model**

I. INTRODUCTION

Stair climbing is among the common physical activities of everyday life. Generally, people use stairs to carry out their normal routine activities. The prolonged usage may result in leg's muscle fatigue and weakness. Weakness is decrease in muscle strength, and fatigue is tiredness, which results due to exertion [1]. Comprehensive analyses of stair climbing could be useful in designing prosthesis, replacement of joint, gait rehabilitation and designing a standard staircase. Force sensors were used to measure the ground reaction forces of the heel and metatarsals by allowing the five healthy subjects to ascend and descend the 3 step variously inclined staircase. There was a huge impact on aging verses inclinations in hip, knee and ankle joint movements [2].

The effects of stair height were investigated on the kinematics and kinetics of stair climbing of 10 normal subjects and found joint ranges and maximum flexion angles that increased with the increase in stair height by designing a staircase that consisted of 5 steps at 3 different inclination angles i.e., 24°, 30°, 42° [3]. A subject-specific knee model was used to study the kinetics of hip and knee joint during stair climbing, estimating bone-on-bone tibiofemoral and patello-femoral joint contact forces. The body weight of a person was greater than the net knee forces while the peak posterior–anterior contact force was closer to it. The posterior-anterior shear forces of the hip and knee and the flexion moment of knee were greater during stair climbing as compared to level walking [4]. The stair ascending and descending action of thirty-three young healthy subjects were compared by designing laboratory staircase. A force platform was used to record the temporal gait cycle data and ground reaction forces. Stair ascent proved to be more demanding biomechanical task as compared to stair descent [5]. In [6], an angle as a new parameter was measured for stair by taking the ratio between the stair height and distance from the feet to the top corner of the stair before the initiation of the leg movement. The biomechanics of lower limb and the effects of increasing the step-height and body mass on it were examined during stair descent by ten male subjects. A four-step staircase having different heights was used in the experiment. Lower limb kinematics, kinetics, EMG of gastrocnemius medialis (GM) muscle and its fascicle length were measured. GM muscle fascicles always shortened, while the muscle–tendon complex (MTC) lengthened in all cases.

The GM muscle fascicles shortened with increase in the height of the step which correspondingly increased the ankle joint moment. By increasing the body mass, no effect on the ankle or knee joint moment during first contact was observed and was supported by trailing leg and hence, the amount of GM muscle fascicle shortening, during the touch-down phase did not alter with increased body mass [7]. In [8], the effect of the progressive walking program on lower limb muscle size and strength and concluded that 17 weeks of progressive walking program thigh muscle size and strength for older adults but added stair climbing exercise does not provide additional training effects.

Therefore, it is imperative to study the mechanism of stair climbing so that certain measures can be taken to reduce the chances of leg injuries such as by predicting a certain stair height for an optimum knee or ankle angle.

II. METHODOLOGY

A stair climbing PASCO ME-7001 leg model was designed.The leg model was constructed in such a way that it mimicked the human leg as shown in Fig.1. Before carrying out experiment, 13 people (8 females and 5 males) having relatively different heights and weights were asked to climb the stairs (16*16 cm). The stairs were designed commercially for the experiment. Each big block i.e. one step stair was measured to be 2 inch in height. For the height of 3 inch, a single block of 1 inch was added to the 2 inch stair to make its height as 3 inch. Similarly, to make 5 inch height step, two steps stairs i.e. 4 inch height were added with 1 inch single block to achieve 5 inches. Similarly, three steps of 6 inches with 1 inch single block were added to make a height of 7 inch while 4 steps stairs of 8 inches were added with a single block of 1 inch to make up a height of 9 inch respectively. The relative angles of human knee were measured with the help of goniometer. The average of all the knee angles calculated were 40º,57º,68º and 76º for each of the four heights of staircase as compared to [3] and shown in Fig.2.

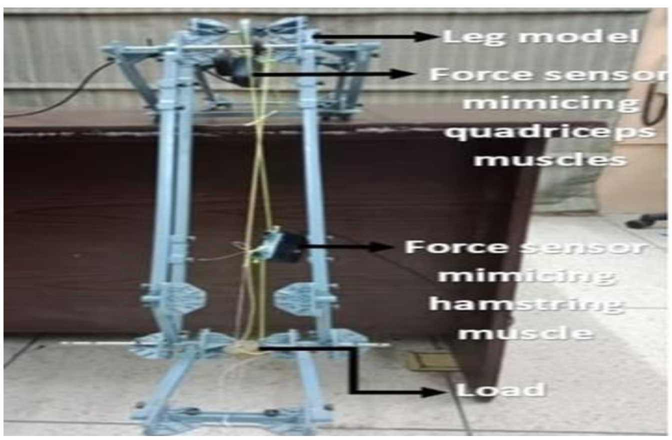

FIGURE 1: Stair climbing model.

The average angles were used for the designed leg model. The forces of the two muscles were mimicked by the tension cords used in the model. Two Force sensors i.e., Force sensor 1 and Force sensor 2 were used, that were connected with PASCO ME-7001, in order to observe the forces applied by both the hamstring and quadriceps muscles at different knee angles, respectively. Force sensor 1 was attached from back of the thigh to the knee joint in such a way that it gave increased force when the leg got flexed. It basically mimicked the force applied on the hamstring muscle during flexion. Force sensor 2 was attached from the front of thigh to the knee of model in such a way that when the leg was extended, the force got increased. This force was applied on the quadriceps muscles during extension. A goniometer was fixed at the side of knee of leg model to observe the flexion and extension of leg model at the desired angles. For each of the four angles, 10 readings were taken with the help of PASCO software on which the force graphs (with respect to time) and the readings were measured.

While taking measurements, initially the model's knee angle was at 0 degree. Then, the knee angle was increased slowly by flexing the knee angle to 40 degrees. The forces on both muscles were observed simultaneously on the software and the trend of graphs was observed for both muscles. After flexion, the model's leg was brought back to the original position and hence, the knee angle was 0 degrees again. The same practice was followed 9 times more to achieve the maximum data of forces applied on the quadriceps and hamstring muscles. The model's leg was now flexed slowly to angle 57 degrees. The values of force and graphs were observed on software for the two muscles by practicing the same method 10 times as that of angle 40 degrees. Similarly, the leg model was flexed slowly at 68 degrees and 76 degrees respectively to observe the values of forces and trend of graphs for the two muscles. The same practice was followed 10 times in the experiment to achieve the maximum data. The experiment is depicted in Fig.3.

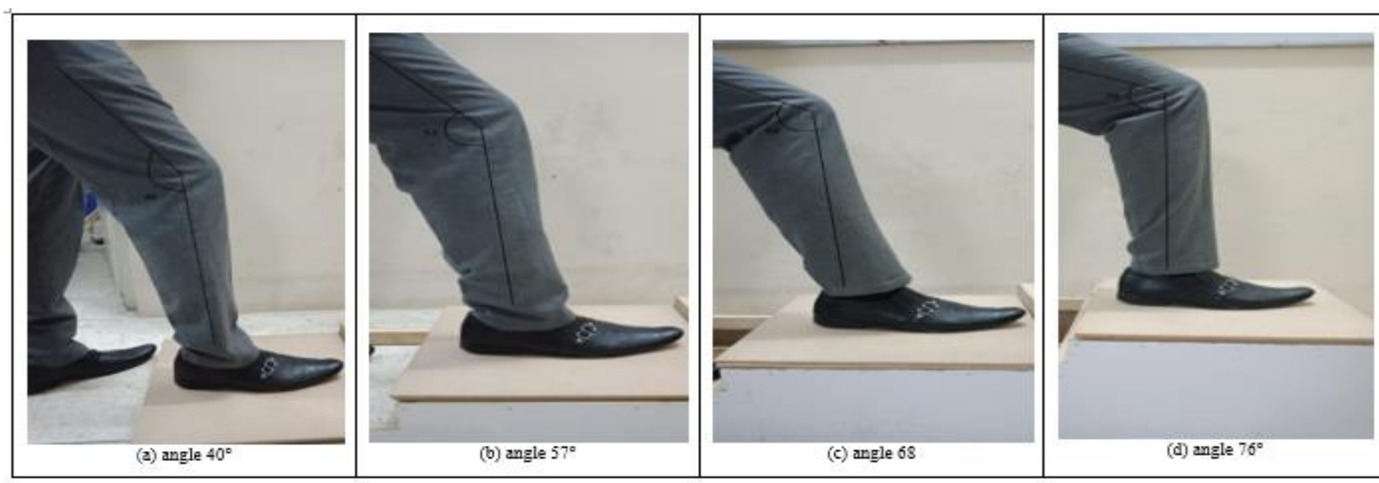

FIGURE 2: (From left to right) Angles calculated for stair heights: 3", 5", 7", and 9"

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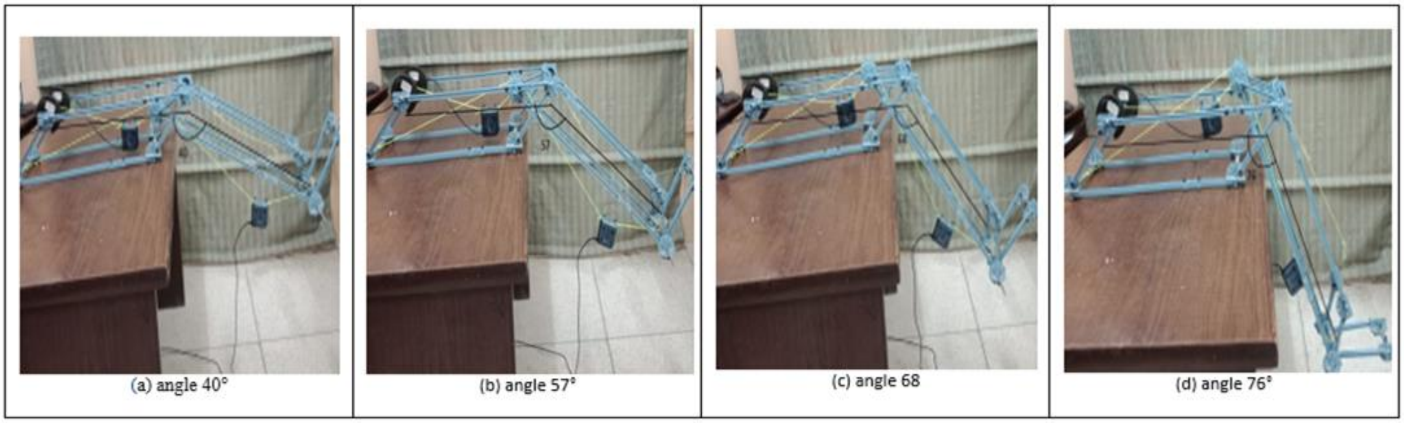

FIGURE 3: (From left to right) Measurements taken using stair height leg model at the angles: 40°, 57°, 68°, and 76°

III. RESULTS AND DISCUSSION

The knee angles that were taken from the female subjects at different stair heights i.e., 3", 5", 7" and 9" are given in table I respectively.

TABLE I: Knee angles measured for females

Subject	Height (inch)	3"	5"	7"	9"
1	5'8"	40°	60°	75°	80°
2	5'4"	40°	60°	80°	90°
3	5'4"	35°	60°	65°	85°
4	4'9"	55°	65°	70°	75°
5	5'5"	49°	65°	78°	80°
6	5'6"	30°	50°	80°	80°
7	5'6"	40°	65°	70°	75°
8	5'7"	48°	65°	75°	75°

Similarly, the knee angles taken from males at different stair heights i.e., 3", 5", 7" and 9" are shown in table II, respectively.

TABLE II: Knee angles measured for females

Subject	Height (inch)	3"	5"	7"	9"
1	6'1"	35°	45°	60°	63°
2	5'5"	45°	60°	45°	80°
3	6'2"	55°	50°	60°	60°
4	6'0"	45°	49°	60°	77°
5	5'8"	45°	50°	55°	77°

Eventually, the average angles of both males and females at desired heights i.e. 3", 5", 7" and 9" calculated were 40°, 57°, 68° and 76° respectively.

A. DURING FLEXION

During the flexion of leg, as the knee angle increases, the force of hamstring muscle increases while that of quadriceps decreases. At angle 40º, maximum resultant force i.e. 14.9 N as shown in Fig. 4 is applied on quadriceps as the model's leg is maximum extended while that of hamstring resultant force is minimum i.e.,8.6 N as the leg is minimum flexed at angle 40º as compared to the other greater angles. With the increase of angle to 57º, the contraction in leg is increased so the resultant force on quadriceps decreases to 11.7 N while that of hamstring resultant force increases to 11.1 N. When the model's leg is further flexed to angle 68º, the resultant force of quadriceps decreases to 11.1 N and as the magnitude of contraction is increased with the angle, the hamstring resultant force also increases to 11.4 N. With the further increase in angle to 76º, there is maximum contraction in model's leg, hence the quadriceps resultant force is maximum decreased i.e. 10.1 N while that of hamstring resultant force is maximum increased i.e. 12.6 N, considering [3] where the maximum knee joint flexion angle changed by 12.1% during ascending stairs.

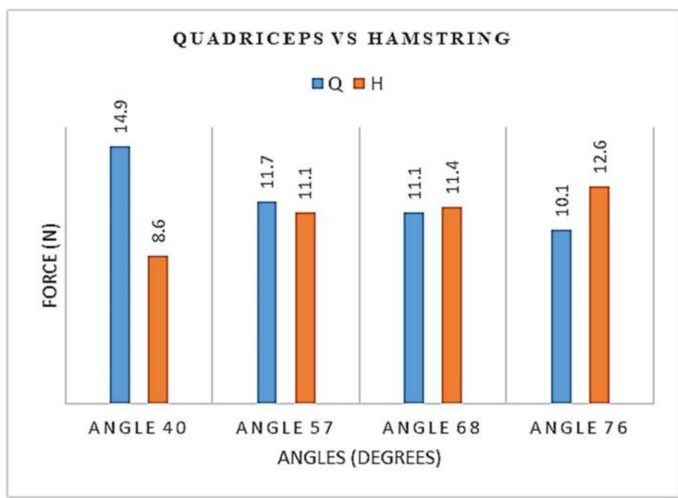

FIGURE 4: Comparison between quadriceps and hamstring muscle during flexion

B. DURING EXTENSION

During extension of leg, the force on quadricep muscles increases with the increase in angle while that of hamstring muscle decreases. At angle 40º, quadriceps apply minimum resultant force i.e. 8.5 N as shown in Fig. 5 because the leg is minimum extended with respect to the other greater angles and the resultant force of hamstring muscle is maximum i.e.14.2 N as there is maximum contraction in model's leg. With the increase of knee angle to 57º, the knee gets more bent at a higher stair height i.e. 5" and its flexion increases, so the knee extensor muscles i.e. quadriceps are more involved in this mechanism and their resultant force increases to 11.0 N while that of hamstring muscle resultant force decreases to 11.1 N. When there is further knee extension to angle 68º, the resultant force of quadriceps increases to 11.4 N and that of hamstring muscle decreases to 10.2 N because of further decrement in its flexion. The maximum resultant force of quadriceps occurs at angle 76º i.e. 12.9 N as there is maximum extension of knee and hence, the quadriceps are more activated. The hamstring resultant force decreases to 8.8 N due to minimum flexion at greatest angle.

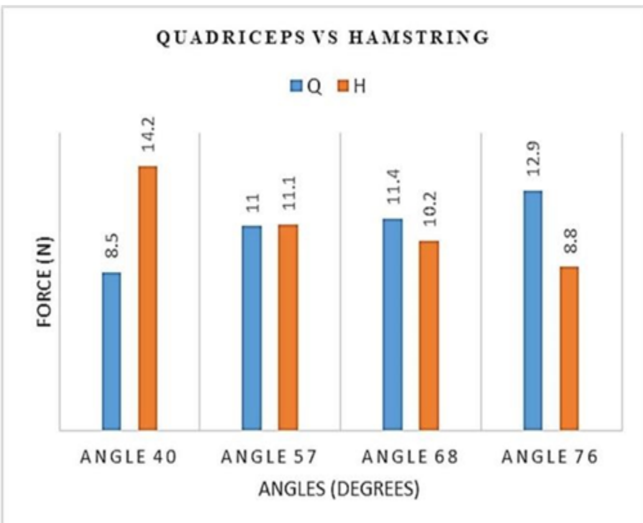

FIGURE 5: Comparison between quadriceps and hamstring muscle during extension

C. ENERGY UTILIZATION BY QUADRICEPS DURING FLEXION

The energy is a quantitative property which helps in doing work. During flexion, as there is more contraction in leg, the quadricepses are less activated, and they consume more energy. The energy consumption of quadriceps at different angles i.e., 40º, 57º, 68º and 76º as shown in Fig.6 respectively is calculated by formula $\Delta F/\Delta T$ in N/s where ΔF is the resultant force and ΔT is the time taken by quadriceps to generate the resultant force. It depicts that as the angle increases, the amount of utilization of energy by the quadriceps decreases. At angle 40º, maximum amount of energy i.e., 7.85 N/s is utilized by the quadriceps as they are more contracted as compared to the other three angles i.e., 57º, 68º and 76º. With the increase of angle i.e., 57º, 6.35 N/s amount of energy is utilized by the quadriceps because as the quadriceps are less contracted as compared to angle 40º. Similarly, at angles 68 and 76 degrees, the amount of energy utilization by the quadriceps decreases to 5.68 N/s and 4.93 N/s respectively as the quadriceps muscle get relaxed with the increase of angle.

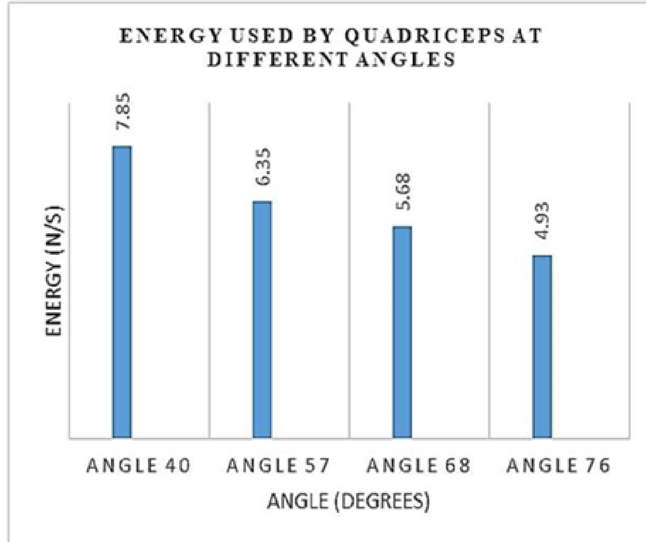

FIGURE 6: Energy utilization by quadriceps

IV. CONCLUSION

This study shows the resultant forces applied on the muscles i.e. hamstring and quadriceps during stair ascent and the amount of energy utilized by the quadriceps with the increase of angles. During flexion, with the increase of knee angle, the resultant force of hamstring muscle increases as it is being contracted while that of quadriceps decreases as it is being relaxed. During extension, with the increase of knee angle, the resultant force applied on quadriceps increases while that of hamstring decreases as more extensor muscles are involved in the mechanism. Furthermore, during flexion, the amount of energy utilized by quadriceps decreases with the increase in knee angle as they get more relaxed with the increase of knee angle. From this study, it can be concluded that the optimum knee angle for stair climbing may be 57 – 68 degrees at 5''– 7" stair height where there is less force exerted on both knee flexor and extensor muscles.

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