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Kinematic Analysis of Human Climbing up and Down Stairs at Different Inclinations

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ABSTRACT

The purpose of this study is to investigate the kinematics in humans during stair climbing and the influence of stair slope variation on gait cycle .The analysis of biomechanical aspect involved in stair ascent and descent can add to our understanding of the diverse and complicated processes involved in human locomotion and also be useful in the design of private and public environments where stairs are employed. Another application is in the field of gait rehabilitation. A comprehensive movement analysis of stair climbing can support the evaluation of joint replacement or prostheses development. A staircase was developed and designed that allowed the collection of kinematic data for multiple steps at different staircase inclinations. All components are characterized by a robust design which minimizes vibrations. Subjects ascended and descended a four-step staircase at three different inclinations (24°, 30°, and 42°). Kinematics was analyzed by a camera-based optoelectronic system. The data were further processed using kinovea and origin pro.8.5 softwares. Hip, knee and ankle kinematics in sagittal plane during stair ascent and descent were reported. Temporal gait cycle parameters were significantly affected by staircase inclination but Joint angles showed a relatively low but significant dependency on the inclination. This study presents a normative database, which could be used as reference data for assessment of stair locomotion.

Keywords: Stair climbing; Ascent; Descent; Kinematics; Stair inclination; Stair gait.

التحليل الحركي لصعود ونزول الانسان لسلّم بدرجات ميل مختلفة

الخلاصة

إنّ غرضَ هذه الدراسةِ هو تحرّي الحركية البشر أثناء تسلّق السلَم وتأثيرِ إختلاف ميل السلَم على دورةِ المشية التحليل الميكانيكي الحيوي الخاص بصعود ونزول السلَم يُمْكِنُ أَنْ يُضيف إلى فَهْمنا العمليات المتنوعة والمعقدة المشتركة في حركة الانسان ويَكُون مفيد أيضاً في تصميمِ البيئاتِ الخاصّةِ والعامّةِ المستخدمة للسلالم التطبيق الآخر في حقلِ إعادةِ التأهيل.ان تحليل الحركةِ الشامل الخاصِ بتسلّق السلَم يُمْكِنُ أَنْ يَدْعمَ تقييمَ تبديل المفاصل أَو تطوير الاطراف الصناعية السلَم صنَع بالشكل الذي يسَمحَ بجمع البياناتِ الحركيّةِ للخطواتِ المتعدّدةِ لزوايا انحدار مختلفة. كُلّ المكوّنات تتميزبالتصميم المتين الذي يُقلّلُ الإهتزازاتَ. الاشخاص تسلقوا صعودا ونزولا السلَم ذوالأربعة

درجات في ثلاثة يول مختلفة (24°,30°و42°)التحليل الحركي حُلّلَ مِن قِبل نظام ضوئي الكتروني أساسه آلة تصوير.البيانات عولجت بإستعمال البرامج(kinovea) و(origin pro.8.5).النتائج المسجلة كانت عبارة عن التحليل الحركي لمفصل الورك,الركبة والكاحل في المستوي الموازي للحركة أثناءإعتلاء ونزول السلّم ،.القيم اللحظية لدورةِ المشيةِ تأثرت بشكل ملحوظ بميلِ السلمِ لكن زوايا المفاصل اضهرتمستوى واطئ نسبياً لكن اعتماد هامّ على الميلِ .هذا البحث يقدم بياناقصطة، والتي يُمْكِنُ أَنْ تستخدم كمرجع للحركة.

INTRODUCTION

Stair climbing is of particular interest in the field of biomechanics and motor control. Since 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 [1]. Increasingly, stairs have become a subject of interest for biomedical researchers, who realize that, even with perfect design, stairs are inherently difficult for humans to navigate, and their use will always lead to accidents[1].Several studies were performed to investigate normal human stair ascent and descent [2-4]. Recently, some researchers focused on the analysis of joint moments [5], joint powers [6] that occur during staircase walking. Some studies also exist that investigate stair climbing of patients with knee [7] and hip [8] implants. Staircase slope proves to be an important characteristic affecting temporal and kinematic gait parameters [9].Our study is a broader attempt to face the question of how staircase inclination affects the kinematic patterns of stair climbing. This knowledge can, for example, serve as a reference for the imitation of natural motor control strategies in intelligent prostheses.

JOINT ANGLES

Studies of stair kinematics have revealed that the greatest ROM occurs in the sagittal Plane [2, 6, 11], with the amount of flexion, particularly at the knee, dependent on stair dimensions [6, 9]. Stair ambulation ROM at the knee requires approximately 10 to 20 degrees more knee flexion compared to that of level walking [2, 3]; furthermore, descent requires about 5 to 10 degrees less ROM than ascent [2]. Similar to that of the knee, the hip joint has a ROM, requiring approximately 15 to 20 degrees more during stair climbing than level walking [2]. During stair descent hip angles range from 20 to 30 degrees at the beginning of stance to 10 to 15 degrees of flexion at the end of stance[2,3]. Similar to that of the hip and knee, the ankle too has a greater ROM in the stance phase. Studies have reported ankle plantarflexion ranging from 10 to 30 degrees and ankle dorsiflexion ranging from 20 to 30 degrees during stair ascent [2,3]; and ankle plantarflexion ranging from 25 to 40 degrees and dorsiflexion 20 degrees during stair descent [2,3,10]. However, difference in the ROM between level walking and stair ambulation could be dependent on the characteristics of the staircase and the individual, with compensations primarily occurring at the knee, and secondary compensations occurring at the ankle and hip [6, 9, and 10].

STAIR GAIT CYCLE

During stair ascent and stair descent, the lower limbs move in a cyclical pattern similar to that of level walking, and the gait cycle for both tasks divided into two phases: the stance (support) phase and the swing phase. Each of the phases is characterized by a distinct length of time spent in the swing and stance phases: stair ascent (66% stance: 34% swing) and stair descent (60% stance: 40%swing)[9].In terms of stair climbing the stance and swing phases are further subdivided into three sub-phases during support and two sub-phases during swing. The stance phase during stair ascent is subdivided into three specific sub-phases: 1) weight acceptance (WA: the initial movement of the body into an optimal position to be pulled up); 2) pull up (PU: the main progression of ascending from one step to the subsequent step); 3) and forward continuance (FC: the complete ascent of a step has occurred and continued progression forward occurs) [3]. The swing phase is subdivided into two specific sub phases: 1) foot clearance (FCL: the bringing of the leg up and over to the next step while keeping the foot clear of the intermediate step); and 2) foot placement (FP: simultaneous lifting of the swing leg and leg positioning for foot placement on step) [3] Figures (1-5). Similar to ascent, the stance phase of descent is divided into three specific sub phases:1) Weight acceptance (WA); 2) forward continuance (FC: the commencement of single leg support and the body begins to move forward); 3) controlled lowering (CL: the major portion of progression when descending from one step to the next) [3]. The swing phase of descent is subdivided into two specific sub-phases: 1) leg pull through (LP: the swing through of the leg); and 2) preparation for foot placement (FP) [3] Figures (6-10).

Figure (1) Weight acceptance phase.

Figure (2) Pull-up phase.

Figure (3) Forward continuance phase.

Figure (4) Foot clearance phase.

Figure (5) Foot placement phase.

Figure (6) Weight acceptance phase.

Figure (7) Forward continuance phase.

Figure (8) Controlled lowering phase.

Figure (9) leg pull through phase.

Figure (10) foot placement phase.

EXPERIMENTAL WORK AND ANALYSIS

Participants

Five healthy young males aged 21 to 28 years participated in the study. . The exclusion criteria were: any neurological problems in the past, diabetes, cardiac or pulmonary diseases, fractures or soft tissue trauma in the lower extremities, trunk or pelvis in the past. The subjects' body stature ranged from 160 to 178.5 cm.

PROCEDURE

The design of the staircase for biomechanics laboratory began by making prototype Figure (11) through which we know the details of changing stairs inclination while maintaining horizontal steps without hindering one other, thus prevent the staircase go down more and obtaining a smaller angle. As well as we know the smallest angle, we can get, and the necessity of spacing between the stairs steps the extent appropriate. The dimensions of the stairs are what would be encountered in a standard building and were based on previous studies [2,6].The important dimensions taken from the literature were the rise and tread for each step which were 17 cm and 29cm, respectively for normal inclination[6]. The staircase Figure (12) consists of four steps made of metal and wood that allowed the collection of kinematic data for multiple steps at different staircase inclinations. All components characterized by a robust design, which minimizes vibrations. Height of staircase can readily adjusted so that the inclination can be varied between 24° and 42°.At a slope of approximately 30°. Since only normal subjects were investigated so no hand railings were necessary. The markers (2 cm in diameter) are placed on the right and left upper iliac crest. Other markers are placed on the following locations of the particular limb under consideration: greater trochanter, lateral femoral condyle, lateral malleolus, and at the foot (fifth metatarsal head).Subjects stood in front of the staircase, ascended, turned, and descended at their Self-selected pace placing only one foot on each step (step-over-step). Kinematic and data were collected specifying the leading leg.Motion was tracked as subjects ascended and descended specially constructed 4-step.

Figure (11) Staircase prototype.

Figure (12) the experimental set-up and the angles arrangement a video camera recorded the spatial positions of Circular passive markers.

DATA PROCESSING AND ANALYSIS

All stride events were expressed as a percentage of the stride cycle .During stair ascent; a stride cycle was defined as first foot contact on the first step and ended at the same foot contact on the third step. During stair descent, the selected stride cycle started with foot contact (of the same foot) on the second step and ended with foot contact (of the same foot) on third one. The analysis performed using kinovea software and data were further processed using origin software performing curve fitting to obtain Joint angles during ascent and descent at minimum, normal and maximum inclinations averaged over all subjects.Gait events were identified and Averaged temporal gait cycle parameters were obtained.Data were expressed as mean and standard deviation (SD) for temporal stride cycle parameters.

RESULTS GAIT CYCLE PARAMETERS

Stride cycle duration normalized from 0% (first contact) to 100% (subsequent contact of the same foot). Differences were observed in the stride cycle durations. They were significantly longer during ascent (1.34–1.40 s) than descent (1.13–1.26 s). They exhibited a tendency to increase with increasing inclination during ascent and descent Table (1).The stance phase was between 58.77 and 63.94% of the cycle duration. During descent, stance duration percentage progressively decreased with increasing inclinations, while during ascent, the stance duration increased only slightly with stair inclinations .on the other hand the double support phase takes the contrast behavior during descent and shows proportional change while increasing inclination.

Table (1) Averaged temporal gait cycle parameters.

Inclination	Cycle durationS.D. (s)	Stance phase S.D. (%)	Double support phase S.D. (%)
Ascent			
Minimum	1.34±0.05	62.23±1.3	11.56±1.3
Normal	1.35±0.08	63.37±2.7	12.21±1.6
Maximum	1.40±1.10	63.94±0.3	14.67±1.6
Descent			
Minimum	1.13±0.12	60.89±0.9	9.4±0.8
Normal	1.14±0.15	59.23±1.8	9.8±0.6
Maximum	1.26±0.12	58.77±1.5	9.9±0.9

ANGLES DURING STAIR ASCENT AND DESCENT

Mean (SD) sagittal plane movements of the hip, knee, and ankle joint during stair ascent and descent illustrated in Figure (13). At minimum inclination during stair ascent in stance phase (from 0% to 62.23% of stride cycle) the hip and knee joints move forwards extension and the ankle joint into plantarflexion while during stair descent in stance phase (from 0% to 60.89% of stride cycle) the hip and knee joints move into flexion and the ankle joint into dorsiflexion. During stair ascent the maximum hip flexion, knee flexion, and ankle dorsi/plantar flexion angles occurred during swing phase (from 62.23% to 100% of stride cycle for stair ascent.

Like minimum inclination ascending the normal inclination with forwards extension movement for the hip and knee and plantar flexion movement for the ankle but in stance phase from (0% to 63.37% of stride cycle) while during descending in stance phase (from 0% to 59.23% of stride cycle) the hip and knee joints move into flexion and the ankle joint into dorsiflexion.

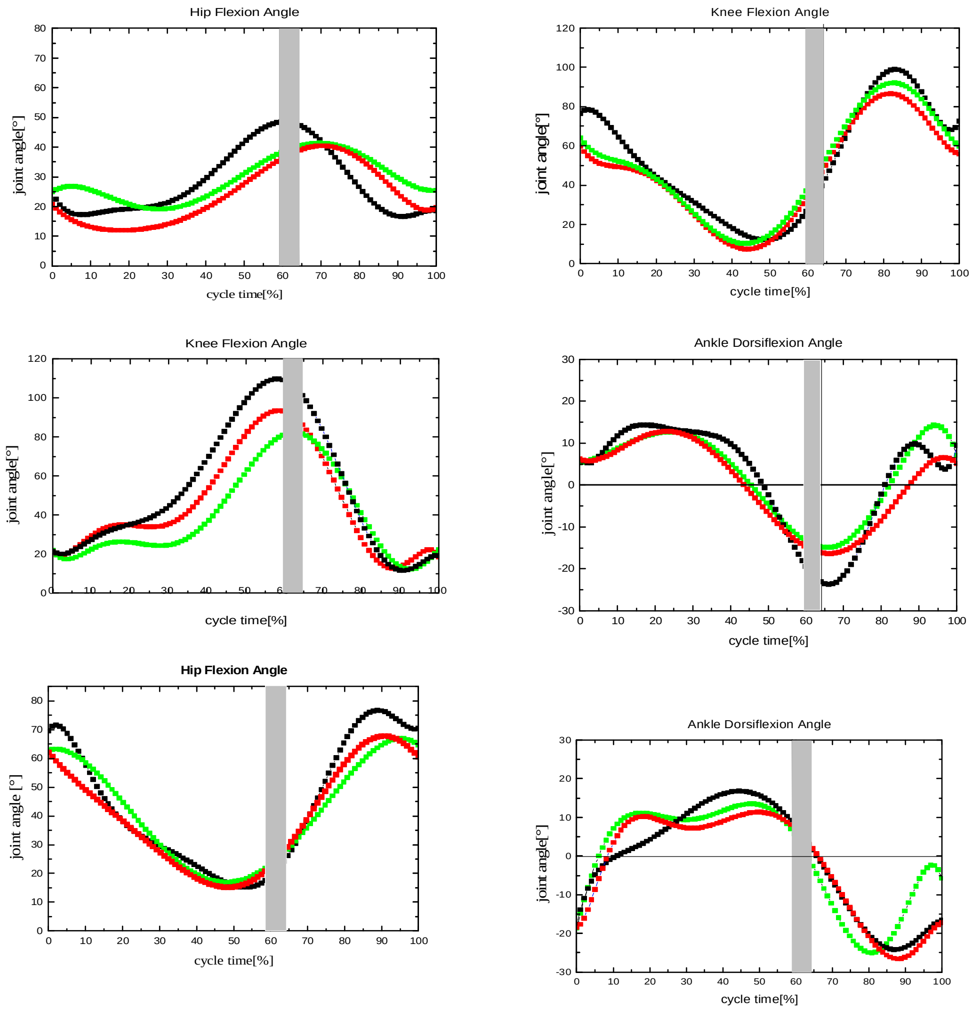

Figure (13) Mean sagittal plane angles of the hip, knee, and ankle joint during ascent and descent at minimum (red), normal (green) and maximum (black) inclinations. The cycle starts with foot contact. The vertical grey bar indicates toe off, thus splitting the entire stride into stance and swing phase. The width of the bar corresponds to the variations of stance phase durations (58.77 - 63.94%) observed for the different inclinations at descent and ascent.

CONCLUSIONS

This paper provides normative profiles of the lower limb during stair ascent and descent at normal inclination that is Similar to findings reported in the literature [2-6] and data that reflect the influence of different inclinations which agree with some basic results presented in [6, 12].Different subject height, step dimension, marker placement, and motion analysis devices may be factors for different results among studies. Number of frame per second analyzed for each subject's stair gait and the appropriate selection of video cutting can affect the final averaged result since it is depending on the visual evaluation.

As the inclination of the staircase increased the joint ranges and maximum flexion angles increased and the maximum knee and hip, flexion angles occurred later during ascent than during descent. Greatest variability was seen in ankle plantar flexion angles during stair ascent. Subjects required greater flexion at the hip and knee joint during stair ascent compared to descent but subjects used less dorsiflexion and plantar flexion at the ankle joint to ascend the stairs compared to descent. The main outcomes of this study indicates that the stair inclination alters ascent and descent joints kinematics and presents an increased range of motion and maximum joint angles as stair inclination increased. This is consistent with the need for a higher elevation of the foot at increased step heights. Thus, it is clear that stair ascent commands greater stability among subjects, as evidenced by stair ascent longer double support and shorter single limb support phases. Since the upward movement is against the gravity stair ascent shown to be the more demanding biomechanical task when compared to stair descent for healthy young subjects.

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