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A Study of Lower-Limb Mechanics during Stair-Climbing*

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ABSTRACT: **The motions, forces, and moments at the major joints of the lower limbs of ten men ascending and descending stairs were analyzed using an optoelectronic system, a force-plate, and electromyography. The mean values for the maximum sagittal-plane motions of the hip, knee, and ankle were 42, 88, and 27 degrees, respectively. The mean maximum net flexion-extension moments were: at the hip, 123.9 newton-meters going up and 112.5 newton-meters going down stairs; at the knee, 57.1 newton-meters going up and 146.6 newton-meters going down stairs; and at the ankle, 137.2 newton-meters going up and 107.5 newton-meters going down stairs. When going up and down stairs large moments are present about weight-bearing joints, but descending movements produce the largest moments. The magnitudes of these moments are considerably higher than those produced during level walking.**

CLINICAL RELEVANCE: **The findings in this study indicate that the forces generated and the functional requirements during stair-climbing should be considered when establishing design criteria for prosthetic devices for weight-bearing joints and when advising patients about their activities.**

Going up and down stairs is a common activity of daily living. From a mechanical viewpoint, it is quite different from level walking. The differences are reflected by changes in the ranges of motion of the different joints during gait, and changes in the phasic muscle activities and in the maximum joint forces and moments. An understanding of the mechanics of stair-climbing is an important step toward greater knowledge of the function of the lower extremities and the pathogenesis of lower-extremity disorders. This information is also needed to improve patient management and to develop criteria for the design of safe joint replacements for the lower extremity.

Kinematic studies have shown that a larger range of knee motion is required during stair-climbing than during level walking[5,7,11]. Using electrogoniometers, Laubenthal et al. observed that about 83 degrees of knee flexion is required to go up and down stairs. Hoffman et al. reported a similar range of sagittal knee motion during stair-climbing in a group of fifty subjects and found that approximately 12 degrees' more knee flexion is required during stair-climbing than during level walking.

Observations of phasic muscle activity[1,6,12,14] have indicated that there are major differences in the activities of the muscles during stair-climbing as opposed to level walking. These differences in activity are mainly in the muscles responsible for vertical movement of the body. Climbing up stairs, the differences are reflected by changes in the contractions of the soleus, quadriceps femoris, hamstrings, and gluteus maximus during the support phase; going down stairs, the differences are reflected by changes in the contractions of the soleus and quadriceps femoris muscles[6,14]. The duration of the activity of the flexor muscles of the knee has been observed to be small compared with the activity of the extensor muscles of the knee, both ascending and descending stairs[12]. Furthermore, the knee extensor muscles are required to generate larger forces during stair-climbing than during level walking. Morrison and Paul confirmed this observation using data derived by means of electromyography, a force-plate, and high-speed moving pictures of three subjects ascending and descending stairs. The information obtained was used to calculate maximum joint forces at the knee, which were found to be 12 to 25 per cent higher than those during level walking. Using an analytical model, Townsend and

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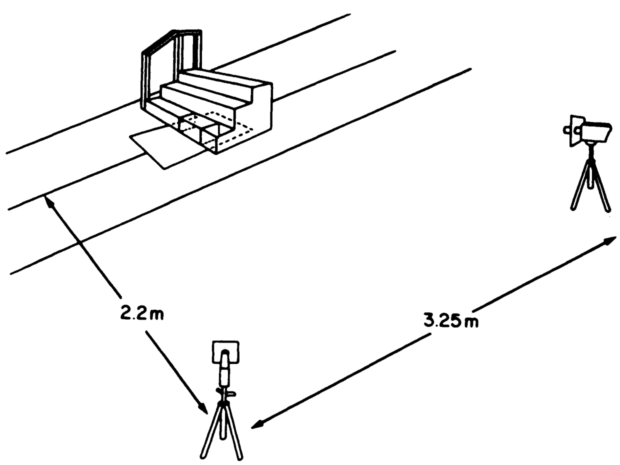

FIG. 1

Camera positions in relation to the staircase and walkway. Note the force-plate and the segment of the first step cut out with a free section resting on the force-plate so that foot-floor and foot-first step reaction forces could be measured.

Tsai[13] observed that a wide range of limb configurations is mechanically feasible during the ascent and descent of stairs. Thus, there is a potential for significant variations in the way different individuals climb stairs.

None of the currently available studies has provided a comprehensive set of data on lower-limb mechanics in normal subjects during stair-climbing. Either the subject populations were small or only a limited number of parameters were studied. The purpose of this study was to analyze the mechanics of the lower limb in ten normal subjects going up and down stairs so that common patterns of motion, forces, and phasic muscle activity could be identified and separated from individual variations.

Materials and Methods

The study was performed on ten men with a mean age of twenty-eight years (range, twenty to thirty-four years). Their weights ranged from fifty-nine to eighty-three kilograms, with a mean of seventy-one kilograms, and their heights ranged from 165 to 193 centimeters with a mean of 179 centimeters. None of the subjects had had previous diseases or injuries of the locomotor system, and no abnormalities were found by examination.

A homogeneous group of test subjects was selected to reduce differences in measurements due to age or body type, since correlations of this type were not among the objectives of the investigation. The subject population was probably more vigorous than an older or disabled group and therefore had joint loads that were larger than those occurring in patients who are likely to have joint replacements.

The instrumentation included a two-camera optoelectronic digitizer (Selspot), light-emitting diodes, a multicomponent force-plate (Kistler), a chart recorder with electromyographic signal conditioning, a minicomputer (PDP 11/40), and a staircase.

The acquisition and processing of the optical and ground-reaction force data were computerized. Eight channels of analog signals from the force-plate were digitized at a rate of 200 samples per second. Simultaneously, the digital signals from each camera were acquired at a frame rate of seventy-five samples per second. Each camera provided two coordinates in the camera reference frame. The three-dimensional positions of the light-emitting diodes were located from the two sets of coordinates using a modified photogrammetric method[2]. A calibration grid containing twenty-nine calibration points was used to provide a reference system for scaling, correction for distortion, and measurement of position. The photogrammetric technique was found previously to be well suited for use with optoelectronic data-acquisition equipment[2]. Using this technique, the system was found to have a resolution of one part in 500.

The two cameras of the optoelectronic digitizer were located on one side of the stairs and were placed symmetrically relative to the force-plate. So placed, they were 2.20 meters from the center line passing along the walkway through the center of the force-plate, and were separated from one another by a distance of 3.25 meters (Fig. 1). This placement was chosen to give three-dimensional views with an adequate viewing range (2.5 meters) as well as to maintain a minimum camera-to-subject distance.

The kinematic parameters for the three major joints (hip, knee, and ankle) were calculated from the three-dimensional positions of six points on each lower

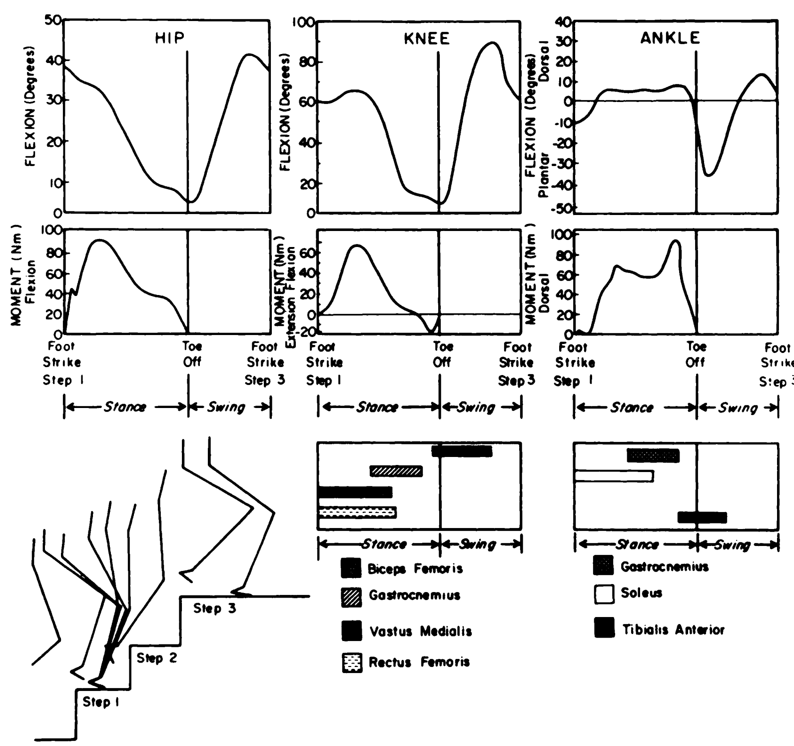

FIG. 2

Sagittal-plane flexion-extension movements of the hip and knee and plantar flexion-dorsiflexion movements of the ankle; moments about these joints; and phasic activities of the knee and ankle muscles in one limb of a subject ascending from Step 1 to Step 3. (The hip muscles were not studied.)

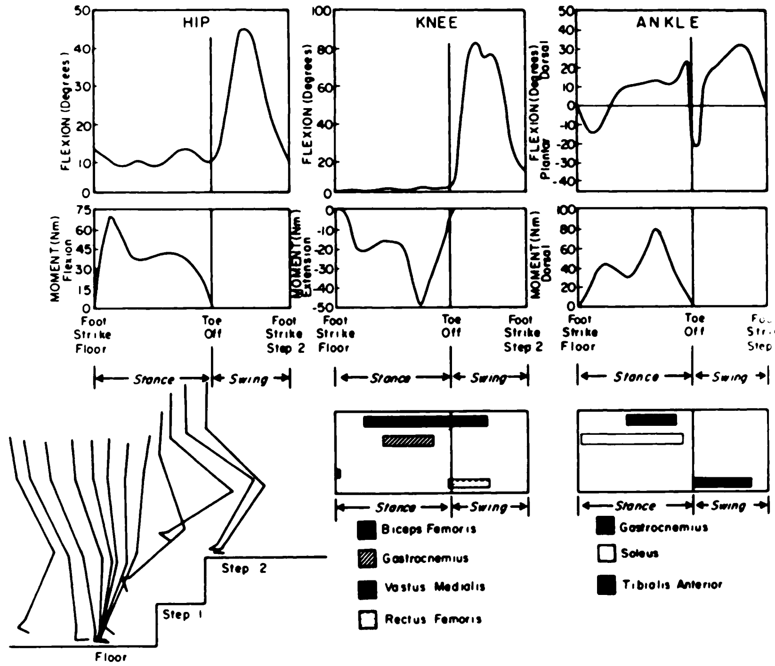

FIG. 3

Sagittal-plane flexion-extension movements of the hip and knee and plantar flexion-dorsiflexion movements of the ankle; moments about these joints; and phasic activities of the knee and ankle muscles in a subject ascending from the floor to Step 2. (The hip muscles were not studied.)

extremity. The points were located by placing light-emitting diodes at the following locations: in the region of the anterior superior iliac spine, over the greater trochanter, over the center of the lateral joint line at the knee, at the lateral malleolus, over the lateral aspect of the calcaneus, and at the base of the fifth metatarsal. Angular joint motions at the hip, knee, and ankle were determined by calculating the angles between vectors defined by the three-dimensional coordinates of the light-emitting diodes located on adjacent limb segments.

The foot-ground reaction force obtained from the force-plate and the instantaneous positions of the hip, knee, and ankle joints were used to compute the net external moment about each joint center throughout stance phase. The moment was calculated by taking the cross product of a vector defining the position of the joint center and of the vector defining the foot-ground reaction force. (Taking the vector cross product is an operation performed on two vectors that yields a third vector perpendicular to the plane defined by the first two vectors. The magnitude of the third vector is equal to the product of the magnitude of the first two vectors and of the sine of the angle between them.) The net vectors of the joint reaction moments were then resolved into component vectors that were aligned along the axes of flexion-extension, abduction-adduction, and internal-external rotation.

The test staircase was composed of three steps, each 25.5 centimeters deep and fifty-eight centimeters wide, with a step height of twenty-one centimeters (standard dimension for an outside staircase). A handrail was placed on the left side. The slope of the staircase was 38 degrees. Outdoor-staircase dimensions were selected because they specify a greater step height and slope than do inside-staircase dimensions, and it was assumed that on these stairs higher physiological demands would be produced. A section of the first step of the staircase was cut out so that this section would rest on the force-plate and permit direct measurement of the foot-stair reaction forces (Fig. 1). It was also possible to measure foot-floor reaction forces directly in front of the first step, using the same force-plate.

Prior to each observation, the subject was instrumented with the diodes already described. The positions of the joint centers of the hip, knee, and ankle in the frontal plane were estimated relative to the diodes placed over the greater trochanter, the lateral joint line of the knee, and the lateral malleolus. The hip-joint center was estimated to be 1.5 to two centimeters distal to the mid-point of a line from the anterior superior iliac spine to the pubic symphysis. The knee-joint center was located in the frontal plane by identifying the mid-point of a line between the peripheral margins of the medial and lateral tibial plateaus at the level of the joint surfaces. The ankle-joint center was estimated to be at the mid-point of a line from the tip of the medial malleolus to the tip of the lateral malleolus.

Bipolar surface electrodes were placed over the rectus femoris, the vastus medialis, the biceps femoris, the medial head of the gastrocnemius, the lateral head of the soleus, and the tibialis anterior muscles. The amplifiers were adjusted following test contractions of each muscle.

Measurements were made while the subjects were ascending and descending the staircase, and observations were recorded while the subjects did and did not use the handrail during the following gait sequences: (1) as the limb moved up from foot-strike on the first step (Step 1) to foot-strike on the third step (Step 3); (2) as the limb moved up from foot-strike on the floor to foot-strike on the second step (Step 2); (3) as the limb moved down from toe-off from Step 3 to toe-off from Step 1; and (4) as the limb moved down from toe-off from Step 2 to toe-off from the floor.

The moments were calculated during the support phase on the first step and on the floor because in these positions the largest inertial contributions were expected.

Results

The data on limb function were separated into those for ascending and those for descending movements, and into those for movements of the limb going up and down from step to step and going from floor to step and from step to floor. Movements and moments in the sagittal plane were described separately from those in the frontal and horizontal planes since movement in the sagittal plane is the primary movement. The sagittal-plane projection of a stick-figure representation of one limb, along with the flexion-extension motions, the moments tending to produce flexion-extension, and the patterns of phasic muscle activity at the knee and ankle of each subject were recorded. Typical ascending (Step 1 to Step 3 and floor to Step 2) and descending (Step 3 to Step 1 and Step 2 to floor to Step 2) patterns were identified (Figs. 2 through 5).

Sagittal-Plane Movements and Moments

Ascending — Step 1 to Step 3

The movements of a single limb ascending from Step 1 to Step 3 are illustrated in Figure 2. When the foot strikes Step 1, the hip and knee joints are flexed and the ankle joint is plantar flexed. As the limb moves from foot-strike to mid-stance, the hip and knee joints extend and the ankle joint dorsiflexes slightly. While the hip and knee joints are extending from the flexed positions that were present at foot-strike, there is an external moment at both joints tending to produce flexion. The knee extensors (vastus medialis and rectus femoris) are active from the time of foot-strike through mid-stance and balance the flexion moment at the knee. Thus, the external flexion moment at the knee is in a direction opposite to the extension movement of the knee, and the extensor muscles are acting both to balance the external flexion moment and to extend the knee. At the ankle joint both the motion and the moment are in the direction of dorsiflexion and the plantar flexors act to balance the dorsiflexion moment. The soleus muscle is active from foot-strike to mid-stance, while the gastrocnemius is active from mid-stance to just before toe-off.

As the limb moves from mid-stance toward toe-off, the hip and knee continue to extend and the ankle plantar flexes during toe-off. At the same time the moment at the hip joint decreases but continues to be in the direction of flexion, and the external moment at the knee changes to extension, the same direction as the movement. The biceps femoris becomes active just before toe-off and remains active through mid-swing until the knee attains maximum flexion. The dorsiflexion moment at the ankle joint reaches a maximum just before toe-off. The tibialis anterior becomes active just before toe-off and remains active until mid-swing phase. From mid-swing to foot-strike on Step 3, the hip joint and knee joint move from a position of maximum flexion toward extension, while the ankle joint moves from a position of maximum dorsiflexion toward plantar flexion. No muscle activity was observed between mid-swing and foot-strike during ascent from Step 1 to Step 3.

Ascending — Floor to Step 2

The movements of a single limb ascending from the floor to Step 2 are shown in Figure 3. These differ from the movements when ascending from Step 1 to Step 3. At the outset, as the foot strikes the floor prior to lifting of the opposite limb up to Step 1, the hip and knee are near full extension and the ankle is plantar flexed. Then, as the limb moves from mid-stance to toe-off, the hip and knee remain nearly fully extended and most of the upward movement results from dorsiflexion of the ankle. The external moment at the hip tends to produce hip flexion throughout the entire stance phase. The external moment at the knee tends to extend the joint, but the knee flexors (biceps femoris and gastrocnemius) are active starting after heel-strike and continuing through all or most of the rest of stance phase. The moment at the ankle, which tends to dorsiflex the joint, reaches a maximum before toe-off, but the soleus remains active from foot-strike until just prior to toe-off, when it ceases to be active. During swing phase the hip and knee reach a position of maximum flexion and then begin to move toward extension shortly before foot-strike. The ankle changes abruptly from dorsiflexion before toe-off to plantar flexion right after toe-off. It then dorsiflexes

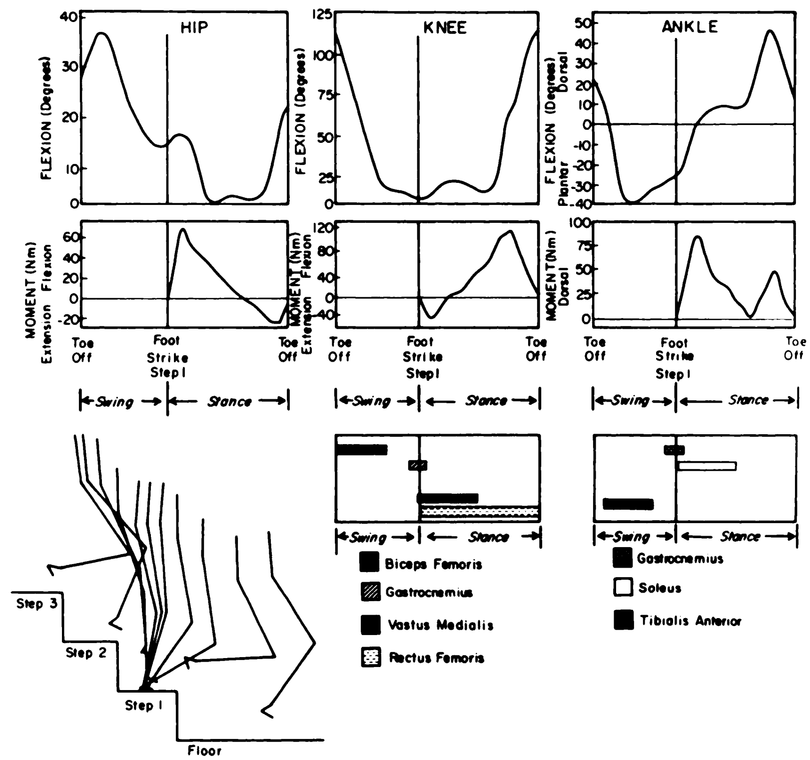

FIG. 4

Sagittal-plane flexion-extension movements of the hip and knee and plantar flexion-dorsiflexion movements of the ankle; moments about these joints; and phasic activities of the knee and ankle muscles in one limb of a subject descending from Step 3 to Step 1. (The hip muscles were not studied.)

TABLE I

Mean of the Maximum Values of Sagittal-Plane Motion (Flexion)*
(In Degrees)

	Stance				Swing			
	Up		Down		Up		Down	
	Step 1 to Step 3	Floor to Step 2	Step 3 to Step 1	Step 2 to Floor	Step 1 to Step 3	Floor to Step 2	Step 3 to Step 1	Step 2 to Floor
Hip	33.8 (6.9)	7.7 (4.6)	13.4 (7.0)	13.2 (6.9)	40.8 (8.7)	41.9 (9.9)	23.0 (10.5)	28.2 (12.9)
Knee	52.5 (5.2)	20.55 (6.8)	68.9 (13.3)	28.9 (16.0)	73.4 (12.4)	83.3 (5.2)	81.6 (11.3)	87.9 (4.4)
Ankle†	13.6 (8.6)	10.0 (7.6)	24.7 (8.9)	27.0 (11.4)	−25.3 (11.5)	−25.1 (10.0)	−25.6 (5.3)	−23.2 (4.0)

* Standard deviation is in parentheses.

† At the ankle joint a positive value indicates dorsiflexion and a negative value indicates plantar flexion.

until mid-swing and finally plantar flexes to neutral prior to foot-strike on Step 2. The biceps femoris and rectus femoris are active during swing from toe-off through mid-swing, while the tibialis anterior is active during the first 80 per cent of swing phase.

Descending — Step 3 to Step 1

The movements of a single limb descending from Step 3 to Step 1 are illustrated in Figure 4. At toe-off from Step 3, the hip and knee are flexed and the ankle is dorsiflexed to a maximum or nearly so. During swing phase, hip and knee flexion decreases and the ankle moves into plantar flexion. The biceps femoris is the only active knee muscle at the start of swing and remains active through mid-swing. The tibialis anterior is active during mid-swing and the gastrocnemius becomes active just prior to foot-strike on Step 1. When the foot strikes Step 1, the hip joint is only slightly flexed, the knee is near full extension, and the ankle is plantar flexed. Then, as the limb moves toward mid-stance on Step 1, the hip joint extends and a simultaneous external hip-flexion moment is present, which must be offset by contraction of the extensor muscles of the hip. (Recordings of the hip muscles were not made in this study.) At the knee there is an external extension moment just after foot-strike, which persists while the knee is flexing slightly. The knee extensors are active from foot-strike throughout the major portion of stance phase on Step 1. The dorsiflexion moment at the ankle reaches a

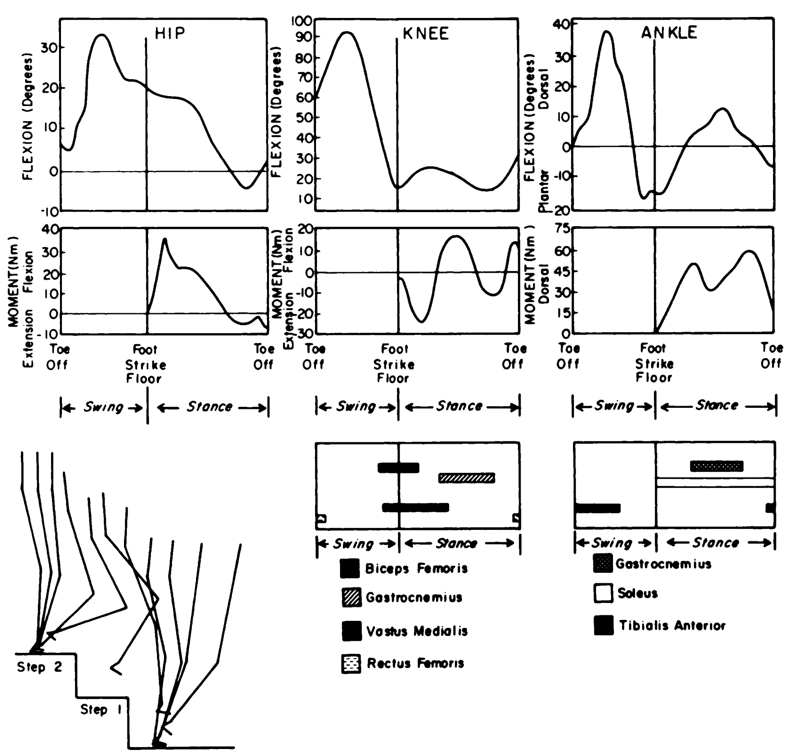

Fig. 5

Sagittal-plane flexion-extension movements of the hip and knee and plantar flexion-dorsiflexion movements of the ankle; moments about these joints; and phasic activities of the knee and ankle muscles in one limb c˜ a subject descending from Step 2 to the floor. (The hip muscles were not studied.)

TABLE II

MEAN OF THE MAXIMUM NET JOINT-REACTION MOMENTS (FLEXION-EXTENSION)*
(IN NEWTON-METERS)

	Up				Down			
	Step 1 to Step 3		Floor to Step 2		Step 3 to Step 1		Step 2 to Floor	
	No Handrail	Handrail	No Handrail	Handrail	No Handrail	Handrail	No Handrail	Handrail
Hip	123.9 (33.6)	107.4 (27.0)	54.1 (22.2)	51.0 (19.4)	112.5 (43.1)	99.2 (26.7)	66.5 (22.0)	75.0 (20.8)
Knee	54.2 (17.2)	52.4 (14.1)	−57.1 (15.1)	−44.7 (20.0)	146.6 (48.0)	139.1 (45.0)	−42.9 (10.0)	−59.6 (26.0)
Ankle	101.8 (38.0)	108.6 (44.0)	137.2 (34.0)	108.1 (40.0)	107.5 (32.0)	104.3 (18.0)	75.5 (12.0)	88.5 (29.0)

* A positive value indicates flexion at the hip and knee and dorsiflexion at the ankle. Negative values indicate extension at the hip and knee and plantar flexion at the ankle. Standard deviation is in parentheses.

maximum while the ankle is moving toward dorsiflexion. Thus, the plantar flexors, which are active until mid-stance, balance the dorsiflexion external moment that is present while the ankle is moving from plantar flexion to dorsiflexion. As the limb moves from mid-stance to toe-off, the hip remains near full extension and the moment at the hip changes toward extension. Prior to toe-off, the knee begins to flex as the external moment tending to flex the knee reaches a maximum and decreases prior to toe-off. Therefore, prior to toe-off, knee flexion is under the control of the knee extensors (rectus femoris) as they act to balance a large external flexion moment at the knee that develops just before toe-off. Maximum dorsiflexion at the ankle occurs just prior to toe-off and is associated with a rise in dorsiflexion moment.

Descending — Step 2 to Floor

During descent from Step 2 to the floor, the limb leaves Step 2 and during swing phase moves toward the floor, while the hip and knee flex and the ankle moves into plantar flexion (Fig. 5). During swing phase, the rectus femoris and tibialis anterior are active at toe-off and during the first part of swing, while the vastus medialis and gastrocnemius become active near the end of this phase. At foot-strike on the floor, the hip is still moderately flexed, the knee is nearly fully extended, and the ankle is plantar flexed. Then, as the limb on the floor moves toward mid-stance, the hip extends, the knee flexes slightly, and the ankle dorsiflexes. At mid-stance the external moment at the hip tends to flex the joint, and the external knee moment changes from extension to flexion. After mid-stance the hip and knee moments change back to extension. Both knee flexors (biceps femoris) and extensors (vastus medialis) are active at foot-strike, and the vastus medialis remains active until mid-stance. The gastrocnemius becomes active during mid-stance as the ankle joint moves from dorsiflexion at mid-stance to plantar flexion at toe-off. Dorsiflexion of the ankle increases during stance phase to reach a maximum during mid-stance and then changes to plantar flexion just prior to toe-off. The soleus is active throughout stance phase.

Maximum Ranges of Flexion-Extension Motion and Flexion-Extension Moments

The maximum ranges of movement and the maximum external moments at the hip, knee, and ankle while ascending stairs were compared with those while descending stairs (Tables I through IV).

Motions

At the hip, the most flexion occurred during swing phase while ascending (41.9 degrees), and at the knee the

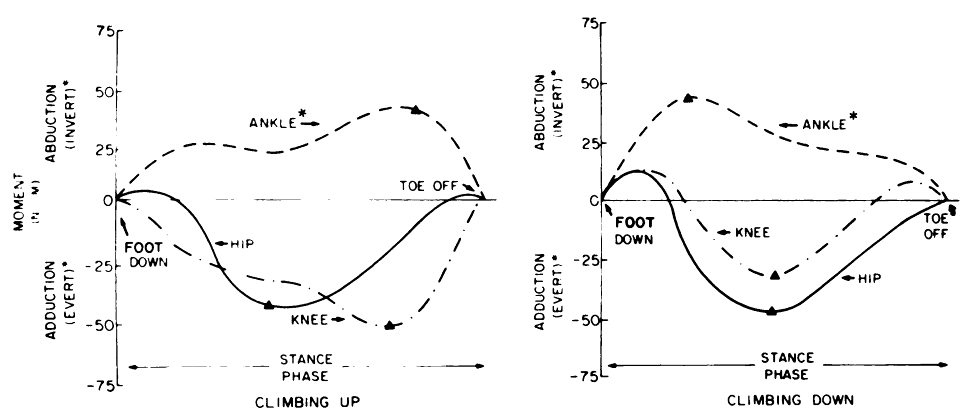

FIG. 6

Typical patterns of abduction-adduction moments at the hip and knee and inversion-eversion moments (*) at the ankle joints. The patterns going up and down from step to step and between floor and step were similar.

TABLE III

MEAN OF MAXIMUM EXTERNAL MOMENTS (ABDUCTION-ADDUCTION)*
(IN NEWTON-METERS)

	Up				Down			
	Step 1 to Step 3		Floor to Step 2		Step 3 to Step 1		Step 2 to Floor	
	No Handrail	Handrail	No Handrail	Handrail	No Handrail	Handrail	No Handrail	Handrail
Hip	−37.0	−36.5	−60.7	−58.4	−40.1	−33.4	−86.0	−63.9
	(18.7)	(20.3)	(28.3)	(28.5)	(23.3)	(12.1)	(31.5)	(23.5)
Knee	−33.0	−28.2	−32.5	−39.4	−23.6	−27.2	−59.5	−38.5
	(17.0)	(9.0)	(21.0)	(18.0)	(16.0)	(11.0)	(37.0)	(18.0)
Ankle	42.8	39.2	22.6	19.4	44.5	47.5	31.3	17.8
	(33.0)	(9.0)	(9.0)	(13.0)	(14.0)	(17.5)	(28.0)	(8.0)

* A positive value indicates abduction at the hip and knee and inversion at the ankle. A negative value indicates adduction at the hip and knee and eversion at the ankle. Standard deviation is in parentheses.

most flexion occurred during swing phase while descending the stairs (87.9 degrees) (Table I). However, there was no significant difference between the amounts of swing-phase hip and knee flexion while ascending and descending stairs.

On the other hand, at the knee there was a significant difference between the amounts of stance-phase flexion during floor-to-step and during step-to-step ascending and descending movements. Thus, during the stance phase while descending, the knee flexed more than twice as much going from step to step (68.9 degrees) as it did going from step to floor (28.9 degrees).

At the ankle joint during swing phase the motion patterns while ascending and descending stairs were similar. During stance phase, on the other hand, dorsiflexion was less while ascending from floor to step (10 degrees) than while descending from step to step (24.7 degrees). The most dorsiflexion (27 degrees) was observed during mid-stance phase while descending from step to step.

Moments

At the hip, the maximum flexion moment (123.9 newton-meters) during ascent was observed while the limb was ascending from Step 1 to Step 3 (Table II), and this moment was reduced by a factor of slightly more than two while the limb was ascending from the floor to Step 2. Step-to-step descent produced a moment at the hip approximately twice that produced by descending from Step 2 to the floor (112.5 compared with 66.5 newton-meters).

At the knee, the maximum flexion moment (146.6 newton-meters) occurred during step-to-step descent. This moment was nearly three times that produced at the knee joint by other activities. Thus, the most stressful activity for the knee joint appears to be step-to-step descent.

At the ankle, both going up and going down stairs tended to produce dorsiflexion-plantar flexion moments that were not significantly different. The activity that produced the largest moment (137.2 newton-meters) at the ankle during stance phase was ascending from floor to step. Using the handrail in the usual fashion had no statistically significant influence on the magnitude of any of the flexion-extension moments observed in this investigation.

Frontal-Plane and Horizontal-Plane Moments

The abduction-adduction and internal-external rotation moments at the hip and knee and the inversion-eversion and internal-external rotation moments at the ankle were analyzed in a similar manner to that described for the flexion-extension moments of these joints. The typical patterns for going up and down from step to step and between floor and step were similar (Figs. 6 and 7).

Abduction-Adduction and Inversion-Eversion Moments

At the hip, the abduction-adduction moment tended to adduct the joint throughout the entire stance phase. The maximum adduction moment of 86.0 newton-meters was observed during descent from Step 2 to the floor (Table III). The adduction moments observed while descending from Step 3 to Step 1 were about half as large as the moments recorded while descending from Step 2 to the floor. At the knee, the maximum adduction moment occurred when descending from Step 2 to the floor (59.5 newton-meters). At the ankle there was an inverting moment throughout the entire stance phase which was maximum (47.5 newton-meters) during descent from Step 3 to Step 1.

Internal-External Moments

The internal-external moments were quite low (less than twenty newton-meters) at all joints during every activity studied (Table IV). The patterns of the internal-external rotation moments were also quite variable. The most common finding (Fig. 7) was an internal rotation moment at the hip and ankle and an external rotation moment at the knee during the stance phase of the activities studied.

Discussion

The net moments at the hip, knee, and ankle were found to be of sufficient magnitude to require that they be considered in any analysis of the mechanics of the lower limb during stair-climbing, and in the design of implants for joint reconstruction. It appears from our results that the

TABLE IV

MEAN OF MAXIMUM EXTERNAL MOMENTS (INTERNAL-EXTERNAL ROTATION)*
(IN NEWTON-METERS)

	Up				Down			
	Step 1 to Step 3		Floor to Step 2		Step 3 to Step 1		Step 2 to Floor	
	No Handrail	Handrail	No Handrail	Handrail	No Handrail	Handrail	No Handrail	Handrail
Hip	14.7	13.4	11.7	10.3	15.6	12.0	18.0	15.1
	(5.5)	(6.1)	(3.8)	(3.0)	(6.1)	(3.2)	(7.7)	(5.4)
Knee	−6.8	−6.4	−7.8	−6.3	−15.1	−15.5	−15.0	−14.3
	(3.0)	(3.0)	(3.7)	(2.0)	(9.1)	(5.3)	(9.0)	(8.0)
Ankle	9.1	9.2	13.2	11.2	10.9	12.0	19.7	13.6
	(6.0)	(4.3)	(4.8)	(5.0)	(4.0)	(5.0)	(8.0)	(2.0)

* A positive value indicates internal rotation and a negative value indicates external rotation. Standard deviation is in parentheses.

flexion-extension moments correlate with the activity of the major flexor-extensor muscle groups, since the net external moments must be balanced primarily by muscle forces.

There is often antagonistic and synergistic muscle activity across a joint prohibiting direct calculation of muscle forces without additional assumptions defining some type of optimization criteria. However, the magnitude of the moment can be used as a relative indicator of the magnitude of the muscle forces across a joint.

Similarly, the contact forces in the joints are directly proportional to the net reaction moments about the joints. Thus, an activity that produces a large external moment will probably produce a large contact force in a joint. It is useful to re-examine the results with these relations in mind.

The ankle joint was subjected to relatively large dorsiflexion moments while both ascending and descending stairs, which necessitated comparable muscle forces in the plantar-flexor muscle group. These dorsiflexion moments were similar in magnitude to those observed during level walking[3,8]. However, the inversion moments while descending or ascending from one step to another were larger in magnitude than those observed during level walking.

At the knee, the flexion moments while descending stairs were the largest and necessitated a large force in the knee extensor muscles to offset them. This flexion moment was about three times greater than the flexion moment generated during level walking. If one assumes that the joint force at the knee is proportional to the external moments at this joint, then the magnitude of the knee-joint contact force generated while descending stairs could be more than six times body weight. The large external moment about the knee while descending stairs occurred when the knee was at about 50 degrees of flexion, whereas during level walking the largest moment occurs when the knee is near full extension[3,8]. Thus, on stairs the knee-joint surface probably sustains a resultant contact force that is different in both direction and magnitude from that occurring during level walking. It should be noted that the flexion-extension moment at the knee when the foot struck the floor while descending from Step 2 was about 50 per cent less than the moment when descending from one step to another, because when stepping down to the floor both feet descend to the same level rather than the swing-phase limb going to the next step below. A patient can reduce the joint forces significantly if both limbs are brought down to the same step while descending from one step to the next.

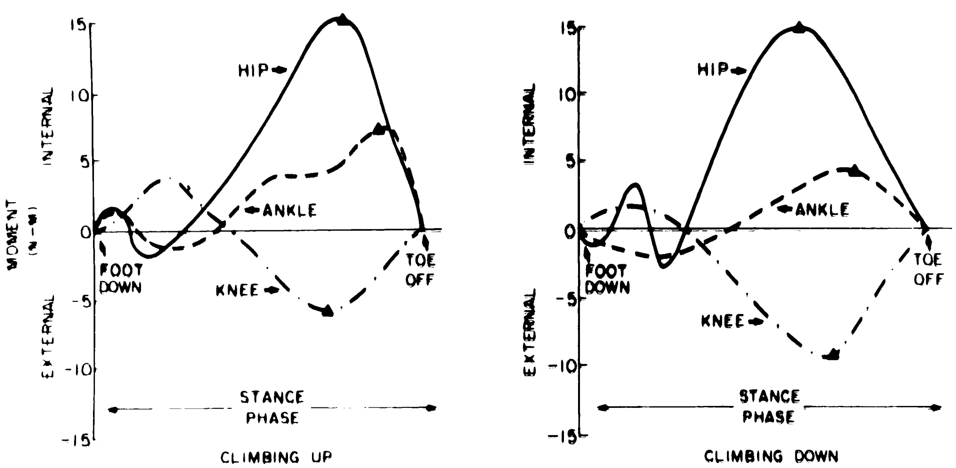

FIG. 7

Typical patterns of internal-external moments at the hip, knee, and ankle joints. The patterns going up and down from step to step and between floor and step were similar.

Many patients descend stairs in this fashion because of the pain associated with the large force generated by placing one foot on every other step as they go down the stairs.

As at the knee joint, the flexion-extension moments at the hip were also found to be larger while descending from one step to another than from one step to the floor. The step-to-step flexion moments were about one and a half times greater than those observed during level walking, whereas the moments while ascending from one step to another were of about the same magnitude as those during level walking. The hip was flexed between 30 and 40 degrees when the largest moments were generated. Thus, the resultant load on the femoral head may have a large force component that is perpendicular to the frontal plane. This component of the load may be an important consideration in the design of the femoral stem of a total hip replacement, since this component could generate tensile stresses on the anterior surface of the femoral stem[4].

Conclusions

The results of this study show that going up and down stairs results in high joint moments. The highest moment usually occurs while descending stairs. The magnitudes of the flexion-extension moments at the hip and knee are greater during stair-climbing than during level walking[3,8]. The largest increase in moment going up and down stairs compared with level walking occurs at the knee joint. The moments at the ankle going up and down stairs do not show any significant increase over level walking. In the development of prosthetic devices for the lower extremity, functional activities such as stair-climbing should be considered among the design criteria.

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