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Biomechanical analysis of body mass transfer during stair ascent and descent of healthy subjects

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Abstract—The purposes of this study were to: 1) assess whole body center of mass (CM) motion in the frontal, sagittal, and transverse planes; 2) compare CM displacement with center of pressure (CP); and, 3) further define the stance and swing subphases of stair ascent (SA) and stair descent (SD) based on critical CM, CP, and ground reaction force (GRF) events.

SA and SD were analyzed on a convenience sample of 11 subjects. Unpaced data were collected from 28 SA trials and 24 SD trials utilizing a bilateral SELSPOT II®/TRACK© data acquisition system and two Kistler force plates at a sampling frequency of 153 Hz. Twenty-six discrete data points were chosen from each trial for analysis. Each identified point detailed the intersection, separation, maximum or minimum value of CM, CP, or GRF in all three planes.

Specific phases of SA and SD are presented and described. The actions of CM, CP, and GRF are presented during each phase. Results further refine the phases originally described by McFayden and Winter. Subtle differences in phases and duration of single and double support are demonstrated between SA and SD. Based on these results, it is apparent that SD is a more dynamic process with greater inherent instability. Knowledge of SA and SD phases and CM/CP dynamics in healthy, normal subjects will permit comparison with patients exhibiting various pathologies. Such comparison should facilitate the development of appropriate intervention strategies.

Key words: *center of mass, center of pressure, gait, ground reaction forces, stairs.*

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INTRODUCTION

The kinetics and kinematics of the normal human gait cycle have been studied extensively (1,2,3). This research has provided a better understanding of the mechanics of normal and pathologic gait, thus improving the design and implementation of rehabilitation programs and assistive devices. Although a few researchers describe lower limb biomechanics during stair ascent (SA) and stair descent (SD), the stair biomechanics literature is scant and incomplete in comparison with that which describes ambulation on level surfaces (4,5,6,7,8). These studies predominantly detail electromyographic (EMG) activity during SA and SD. Minimal discussion is presented regarding kinematics and temporal phases of SA and SD.

The most complete stair locomotion description to date was reported by McFayden and Winter (9), analyzing the biomechanics and temporal phases of SA and SD in three normal subjects. No literature, however, is available that describes the displacement of the body's center of mass (CM) during SA and SD. To have a fuller understanding of the dynamics of purposeful, complex human movements, it is necessary to understand CM dynamics. Only by having a full understanding of the dynamics of SA and SD in healthy "normal" subjects can patients with various pathologies be assessed adequately and appropriate intervention programs be designed.

The purposes of this SA and SD study were to: 1) assess the whole body center of mass antero-posterior, vertical, and lateral motions; 2) compare CM displacement with force plate center of pressure data (CP); and, 3) further define the subphases (stance and swing) of SA and SD based on CM, CP, and ground reaction forces (GRF).

METHODS

Subjects. Data from SA and SD were analyzed from a convenience sample of 11 healthy individuals (3 males, 8 females). **Table 1** summarizes the age, height, weight, and number of trials of data used for analysis. No subjects had any type of musculoskeletal dysfunction that would hinder performance. All subjects reviewed and signed consent forms consistent with institutional policy regarding research on human subjects.

Instrumentation. To assess SA and SD quantitatively, the body was treated as consisting of 11 rigid body segments, each with 6 degrees of freedom. A bilateral SELSPOT II®/TRACK© data acquisition system, two Kistler piezoelectric force plates, a PDP 11/60 minicomputer, TRACK* software, and a Vaxstation II were utilized for data collection, processing, and analysis. CM, CP, and GRF were acquired concurrently at a sampling frequency of 153 Hz. Sampling frequency was determined based upon the number of infrared light emitting diodes utilized in the system (10). Because this frequency is adequate to analyze gait during locomotor activities (10), we deemed it adequate to analyze the slower occurring events of SA and SD. Specifics of this system have been previously described (11).

Stair Construction. The four experimental stairs were constructed using eight box modules. Steps were 28 cm in depth. The rise of the first step was 2.5 cm (to help initiate steady state stepping activity), while the rise of each subsequent step was 18

*This software was developed at the Massachusetts Institute of Technology, Cambridge, MA.

Table 1.
Subject List.

	Age	Sex	Ht.	Wt.	Number of Trials Ascent	Number of Trials Descent
1.	27	F	68	130	1	0
2.	28	F	62	122	3	4
3.	28	F	60	117	4	3
4.	27	F	62	120	2	0
5.	26	F	60	115	4	4
6.	26	M	69	165	3	4
7.	30	F	67	130	0	1
8.	27	M	68	150	4	4
9.	70	F	64	118	4	0
10.	59	F	62	130	1	2
11.	28	M	68	165	2	2
Mean	34.2		64.9	134.9	*Total* 28	24
SD	15.2		3.8	20.0		

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cm (12). The two Kistler force plates were located directly under steps two and three. Hand rails were not available for subject use (**Figure 1**). No platform was present at the top of the stairs for subjects to continue their locomotion.

Protocol. Four trials of SA and SD were performed by each subject. Subjects were allowed to ascend and descend the experimental stairs in whatever manner they felt their natural cadence to be. Data were collected from both left and right extremities as the initial limb of contact. One stride per trial was analyzed for SA beginning with contact on the second step and ending with subsequent contact of the same foot on step four. During SD, trials were analyzed beginning with step three and ending on step one. Three seconds of data were collected during each trial of SA or SD. Each subject was instructed as follows: "Walk up (down) the stairs as you usually do. Stop when you reach the top (bottom)."

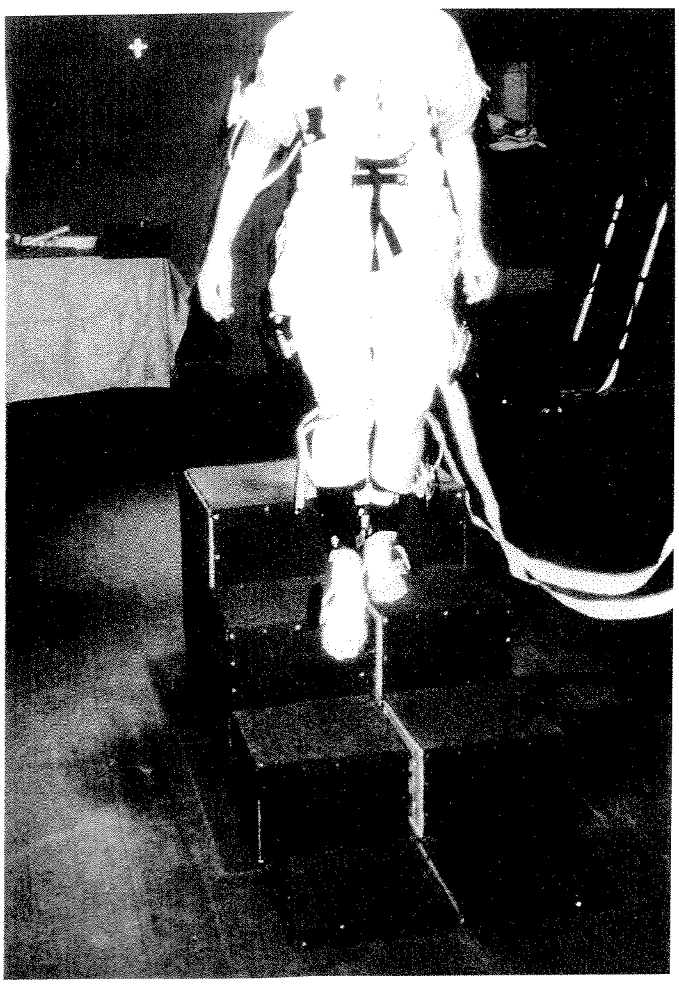

Figure 1.
Photograph of subject and stairs. Kistler force plates are located under stairs two and three.

Data Reduction and Analysis. The force plates, synchronized to the SELSPOT system (Selspot Systems LTD., Troy, MI), were used to determine the GRF, CP, and the initiation and cessation of the stance phase of SA and SD.

Twenty-six discrete data points from each trial were chosen for analysis. Points where the GRF of each foot intersected, maximum and minimum GRF values; maximal values of divergence or convergence between the whole body CM and CP; and points where vertical CM initiated or ceased movements were used (**Table 2**).

Each subject was requested to complete four trials of SA and SD, except Subject #11 who completed only two trials. A total of 42 trials of SA and 42 trials of SD were attempted by the subjects. From this total, 28 trials from 10 subjects were used for SA analysis and 22 trials from 8 subjects for SD analysis (**Table 1**). Trials not used in data analysis were the result missing, incomplete, or inadequate data, resulting from constraints in data collection time (3 seconds); compensatory movements during some trials to maintain balance upon reaching the top step during stair ascent (owing to the lack of a platform at the end of the top step); or going out of the system viewing volume. Examples of the data plots from which the 26 discrete data points were chosen are presented in **Figure 2** for ascent and **Figure 3** for descent.

The initiation of stance phase was determined from the force plates. Knee flexion angle was also determined at that time. Stride termination was determined by finding same knee flexion angle on the subsequent SA or SD stride.

RESULTS

Stair Ascent

Phases. Temporal phases are described from each stride normalized from 0% (first contact) to 100% (subsequent contact of the same foot). Normal SA includes both stance and swing phases (**Table 3, Figure 4**). The entire stance phase averaged 65% ± 4% of the SA cycle. Stance subphases include: foot contact (0–2% SA cycle); weight acceptance (0–17% SA cycle); vertical thrust (2–37% SA cycle); single limb support (17–48%); forward con-

Table 2.
Data Points.

ANTEROPOSTERIOR GROUND REACTION FORCE TRACING
Maximum Anterior GRF
Intersection AP GRF with zero line foot B
Maximum Posterior GRF
VERTICAL GROUND REACTION FORCE TRACING
Maximum Vertical GRF #1
Minimum Vertical GRF
Maximum Vertical GRF #2
Intersection Vertical GRF foot A and foot B
Initial deflection Vertical GRF foot A
Loss of deflection Vertical GRF foot A
Initial deflection Vertical GRF foot B
Second contact foot A-determined by identical knee flexion angle as demonstrated during initial deflection Vertical GRF foot A
LATERAL GROUND REACTION FORCE TRACING
Maximum Lateral GRF #1
Minimum Lateral GRF
Maximum Lateral GRF #2
ANTEROPOSTERIOR CENTER OF GRAVITY/CENTER OF PRESSURE
Intersection AP CG/CP #1
Separation AP CG/CP #1
Intersection AP CG/CP #2
Separation AP CG/CP #2
Intersection AP CG/CP #3
VERTICAL CENTER OF GRAVITY
Initial low point VCG following initial contact foot A
Initial high point VCG
Second low point VCG
Second high point VCG
LATERAL CENTER OF GRAVITY/CENTER OF PRESSURE
Initial maximal LCG displacement
Intersection LCG/CP
Second maximal LCG displacement

tinuance (37–51% SA cycle); and double support (48–65% SA cycle) (**Table 3**).

Foot contact is calculated from the initial deflection of the force plate (0%) until there is a rise in the vertical CM (2% of cycle). Weight acceptance refers to the period of stance limb loading from first contact (0%) until single limb support is attained (17%). Vertical thrust is similar to "pull up" described by McFayden and Winter (9).

Double support occurs during the initial 17% of vertical thrust (vertical CM displacement). The remainder of vertical thrust (17–37%) and the majority of forward continuance (37–48%) occur within single limb support phase. Swing phase consists of foot clearance (clearing the lip of the next step) and foot placement.

Center of Mass (CM). The whole body CM is displaced vertically throughout vertical thrust in stance phase. During forward continuance, no further vertical CM displacement occurs. The CM lateral displacement describes a sinusoidal curve in the frontal plane (**Figure 5**). Maximum displacement (4.4 ± 1.2 cm) in any given subphase occurs at mid stance (34% SA cycle), during the vertical thrust subphase. There follows a rapid direction reversal, and weight is transferred to the opposite extremity following opposite foot strike during the middle of double support (59% SA cycle). The CM is displaced anteriorly throughout SA (**Figure 6**).

Center of Mass versus Center of Pressure (CP). Mediolateral CM and CP positions begin to diverge at initial foot contact reaching the first of two maxima just prior to the initiation of single limb support (17% SA cycle) (**Figure 7**). Convergence occurs until mid stance (34% SA cycle), just prior to forward continuance. At the time forward continuance begins, the mediolateral CM and CP again diverge, reaching their second maximum at the beginning of double support (48% SA cycle). Once double support is initiated, there follows rapid convergence between CM and lateral CP. The mediolateral CM and CP converge in mid double support (59% SA cycle).

Anteroposterior CM and CP positions diverge as the CM moves anterior relative to the CP. The CM continues its anterior progression relative to the CP until single limb support begins (17% SA cycle). At this time, CP begins and continues its movement anteriorly throughout the forward continuance phase, reaching its maximum anterior displacement,

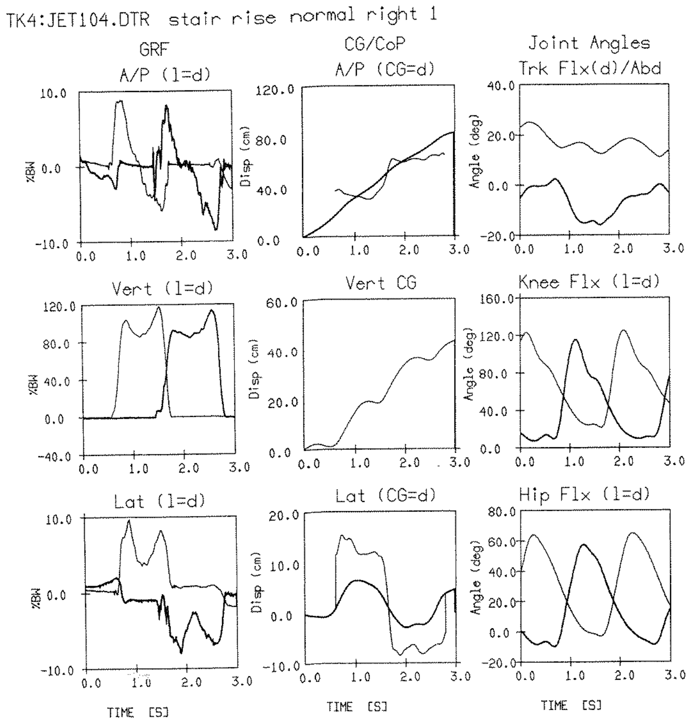

Figure 2.

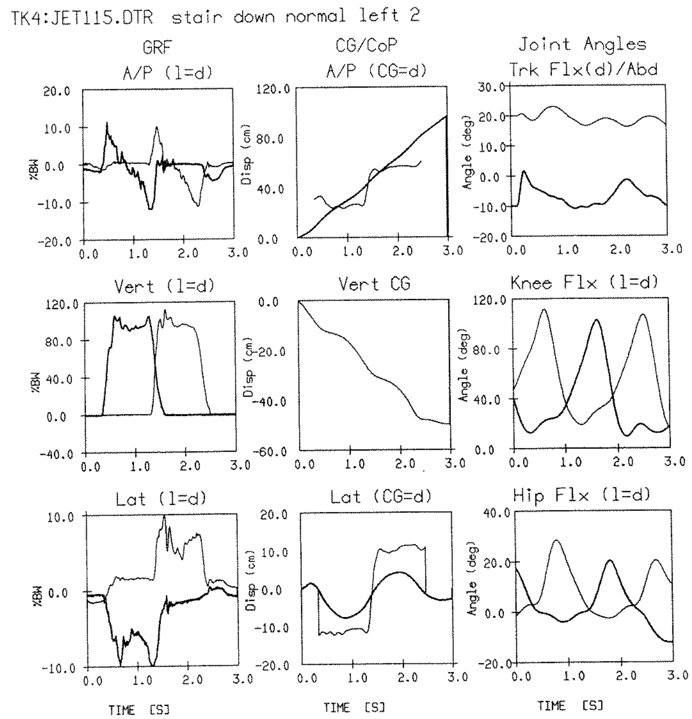

Figure 3.

Figures 2 and 3.
Examples of plots produced from data acquisition and analysis system. Specific data points utilized in this study were determined from these plots. Deviations of graph lines up or in the positive direction correspond to anterior, flexion, or to the right.
TK4:JET104.DTR—stair rise normal, right 1. Subject reference number, leading extremity and trial number.
TK4:JET115.DTR—stair down normal, left 2. Subject reference number, leading extremity and trial number.
GRF, Ground Reaction Force; CG/CoP, Center of Gravity/Center of Pressure; A/P, Anteroposterior; Vert, Vertical; Lat, Lateral; (l = d), Left Extremity (*dark line*); (CG = d), Center of Gravity (*dark line*); Trk Flx (d), Trunk flexion relative to ground (*dark line*); Abd, Abduction of the trunk relative to ground; Knee Flx, Knee Flexion; Hip Flx, Hip Flexion; %BW, Percent Body Weight; Disp (cm), Displacement in centimeters.

relative to CM, as double support is initiated (48% SA cycle). During double support, the CP moves rapidly posteriorly, intersecting with the CM at the mid portion of double support (59% SA cycle). Movement of CP posteriorly continues until the end of the stance phase of SA (65% SA cycle). At that time, only the opposite foot is loaded, and the CP moves anteriorly (**Figure 7**).

Ground Reaction Forces (GRF). At foot contact, there is a rapid increase in the vertical GRF, reaching the first of two maximums at the start of single limb support (17% SA cycle)(**Figure 8**). Vertical GRF gradually decreases until mid stance (34% SA cycle), after which it again increases, reaching its second maximum as double support is initiated (51% SA cycle). The magnitude of the mediolateral shear component of the GRF (lateral GRF) increases from foot contact until single limb support (17% SA cycle), reaching the first of two maximums. Lateral GRF, like vertical GRF, gradually falls until mid stance (34% SA cycle). After mid stance, it again increases, reaching its second maximum at the initiation of double support (51% SA cycle). At foot contact, the magnitude of the anteroposterior shear component of the GRF (A/P GRF) is initially directed posteriorly (−0.4% body weight). By the end of the foot contact phase (2% SA cycle), this force has reversed direction and is now directed anteriorly. Maximum anterior shear is reached during weight acceptance. Just prior to single limb support, A/P GRF is again directed posteriorly, crossing the zero position as forward

Table 3.
Temporal phases of SA as % of total cycle.

	Start		Finish	
	Mean	**SD**	**Mean**	**SD**
Stance	0	0*	65	4
Foot Contact	0	0*	2	6
Weight Acceptance	0	0*	17	3
Vertical Thrust	2	6	38	4
Single Limb Support	17	3	48	4
Forward Continuance	38	4	51	4
Double Support	48	4	66	4
Swing	65	4	100	0*
Foot Clearance	65	4	82	4
Foot Placement	82	4	100	0*
Critical Points				
Mid Stance	34	5		
Mid Double Support	59	4		
Cycle time (seconds) 1.662 ± .371				

*By definition.

continuance is initiated. The greatest posterior shear force is reached 56% into SA (**Figure 8**, triangle between 51% and 59% SA).

Stair Descent

Phases. Temporal phases are also described from each stride, normalized from 0% to 100% (**Table 4, Figure 9**). During stair descent (SD), stance phase comprises 68% ± 2% of the total SD cycle and may be subdivided into weight acceptance (0–14% SD cycle), forward continuance (14–34% SD cycle), and controlled lowering (34–68% SD cycle).

Like SA, weight acceptance involves stance limb loading until single limb support is attained. During forward continuance, the whole body CM is progressed forward but does not undergo any vertical translation. During controlled lowering, the whole body CM is lowered in the transverse plane.

Single limb support accounts for 39% of the stance phase (14%–53% of each cycle). Double support occurs at the beginning and end of stance phase, 0–14% and 53–68%, respectively. Swing phase comprised the remaining 32% of SD and is divided into leg pull through (68–84% SD cycle) and foot placement (84–100% SD cycle) (**Figure 9**). Swing phase has been appropriately described by McFayden and Winter (9).

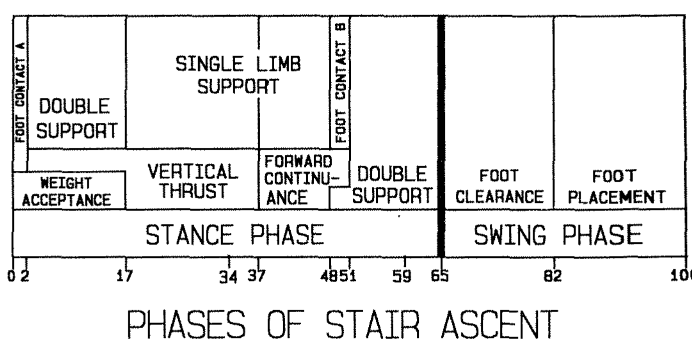

Figure 4.
Phases of Stair Ascent (SA). Numbers along baseline represent percentage cycle spent in each phase or subphase from initial contact of foot A with the stairs (0%) to the next contact of foot A with the stairs (100%). Use of dual force plates allows detailing of initial contact of foot B with stairs (48%) and determination of double support phase.

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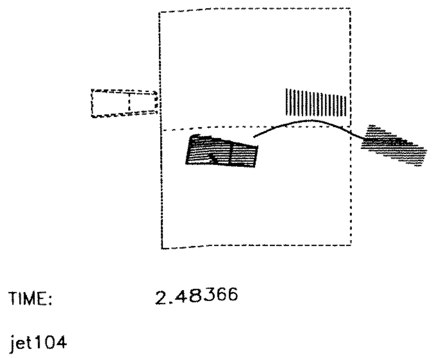

Figure 5.
Graphic plot demonstrating sinusoidal path of center of gravity while ascending stairs. Note that the center of gravity is within the base of support (not within the perimeter of the foot) during stair ascent.

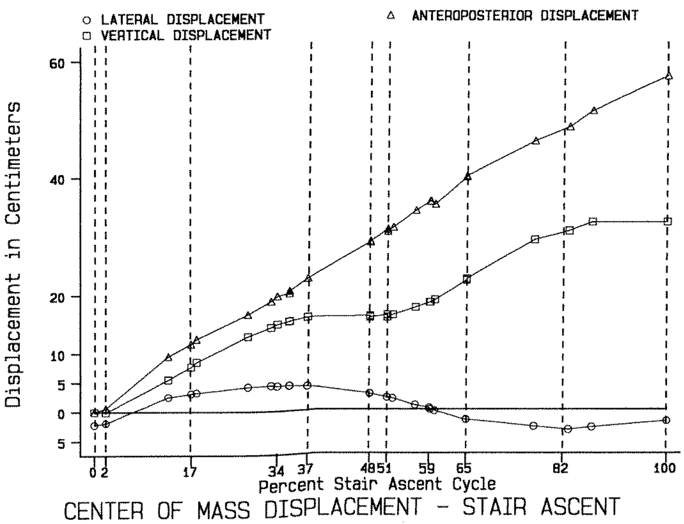

Figure 6.
Center of Mass Displacement—Stair Ascent (SA). Displacement of the Center of Mass (in centimeters) is graphed in all three planes during the phases of stair ascent. Points indicated on the graph are data.

Center of Mass. The center of mass (CM) vertical position descends during the weight acceptance portion of stance phase. Similar to SA, during forward continuance, no further downward displacement occurs. During controlled lowering, the CM again descends. The CM is displaced anteriorly throughout SD (**Figure 10**).

Laterally, the CM position follows an approximately sinusoidal curve in the frontal plane (**Figure 11**). Maximum mediolateral displacement of the CM (4.2 ± 1.4 cm) occurs at mid stance (32% SD cycle). This occurs near the end of forward continuance (34% SD). Immediately after forward continuance,

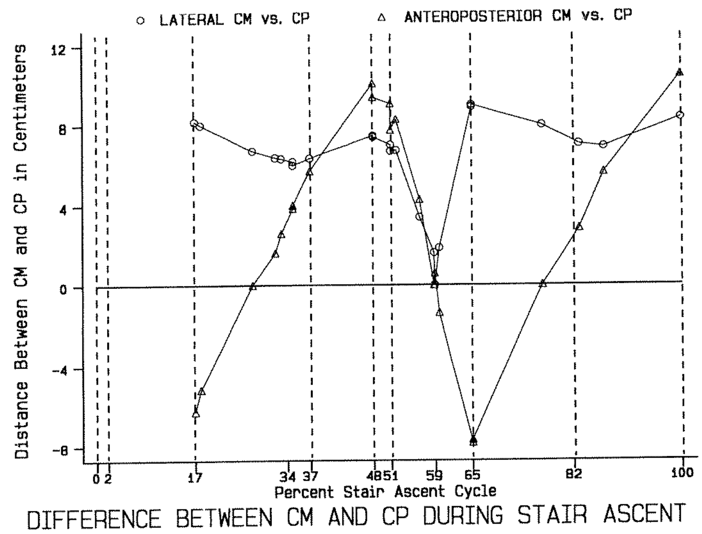

Figure 7.
Difference Between CM and CP During Stair Ascent. The distance between the CM and CP in the frontal and sagittal planes is graphed. Because of limitations imposed by the viewing volume computations were limited for the first 14 to 17% of the cycle; therefore, no values are presented. Points indicated on the graph are data.

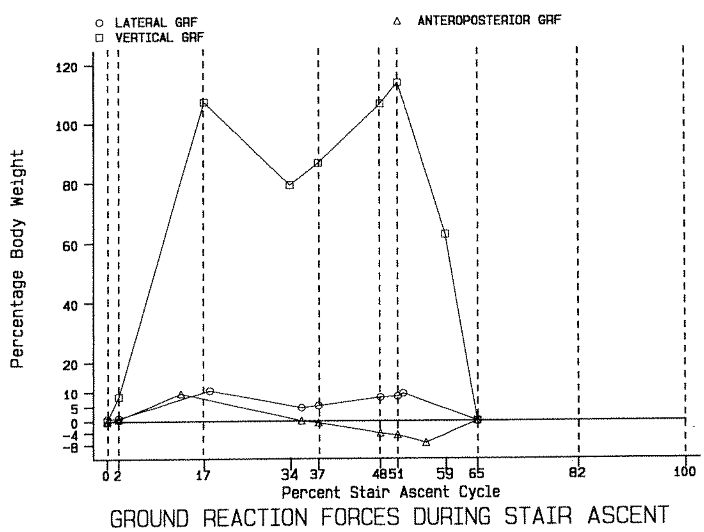

Figure 8.
Ground Reaction Forces During Stair Ascent. GRFs during stair ascent as a percentage of body weight are graphed. Points indicated on the graph are data.

the CM travels medially, until the CM and CP are coincident at mid double support (58% SD cycle).

Center of Mass versus Center of Pressure. During stair descent, mediolateral center of mass and center of pressure demonstrated similarities to stair ascent (**Figure 12**). Maximum CM versus CP

Table 4.
Temporal phases of SD as % of total cycle.

	Start		Finish	
	Mean	**SD**	**Mean**	**SD**
Stance	0	0*	68	2
Weight Acceptance	0	0*	14	6
Forward Continuance	14	6	34	14
Single Limb Support	14	6	53	3
Controlled Lowering	34	14	68	2
Double Support	53	3	68	2
Swing	68	2	100	0*
Leg Pull Thru	68	4	84	13
Foot Placement	84	13	100	0*
Critical Points				
Mid Stance	32	7		
Mid Double Support	58	3		
Cycle Time (seconds) 1.621 ± .269				

*By definition.

divergence occur for both anteroposterior and mediolateral CM at the beginning and end of single limb support. The mediolateral CM and CP positions intersect at 58% SD cycle, during double support. At foot strike, the anteroposterior CM position moves anteriorly relative to the CP in the sagittal plane. The CP continues its progression posteriorly until the initiation of single limb support. At that time, CP is anterior to the CM. There is a slight deviation in this anterior progression of CP at mid stance. The CM and CP positions converge in the sagittal plane at 58% SD cycle (**Figure 12**).

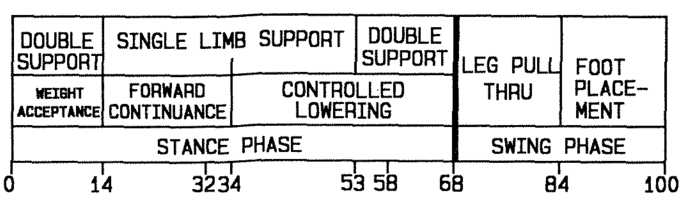

Figure 9.
Phases of Stair Descent (SD). Numbers along baseline represent percentage cycle spent in each phase or subphase from initial contact of foot A with the stairs (0%) to the next contact of foot A with the stairs (100%). Use of dual force plates allows detailing of initial contact of foot B with stairs (53%) and determination of double support phase.

Ground Reaction Forces (GRF). At foot contact, there is a rapid increase in vertical GRF,

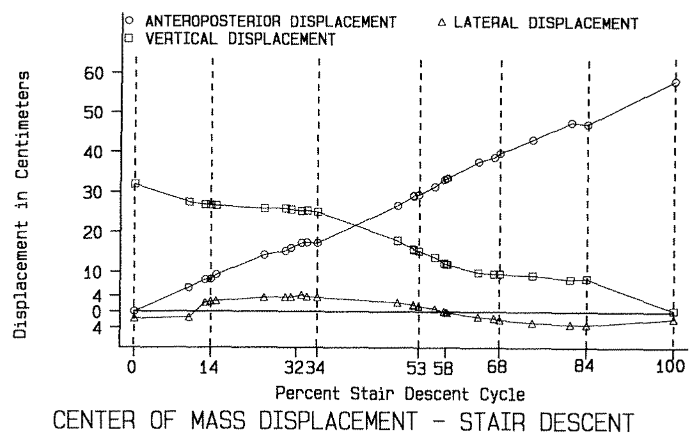

Figure 10.
Center of Mass Displacement—Stair Descent (SD). Displacement of the Center of Mass (in centimeters) is graphed in all three planes during the phases of stair descent. Points indicated on the graph are data.

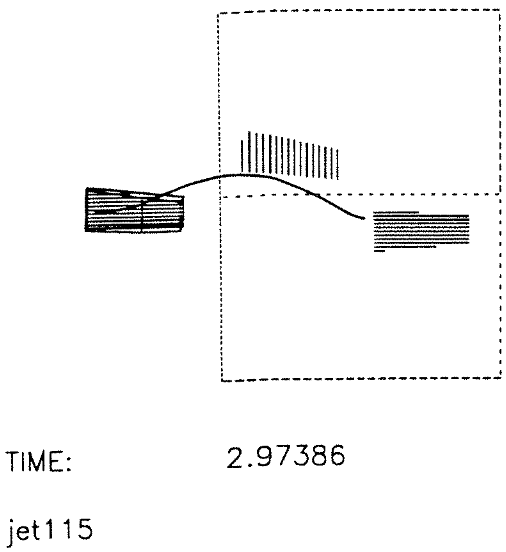

Figure 11.
Graphic plot demonstrating sinusoidal path of center of gravity while descending stairs. Note that the center of gravity is within the base of support (not within the perimeter of the foot) during stair descent. Points indicated on the graph are data.

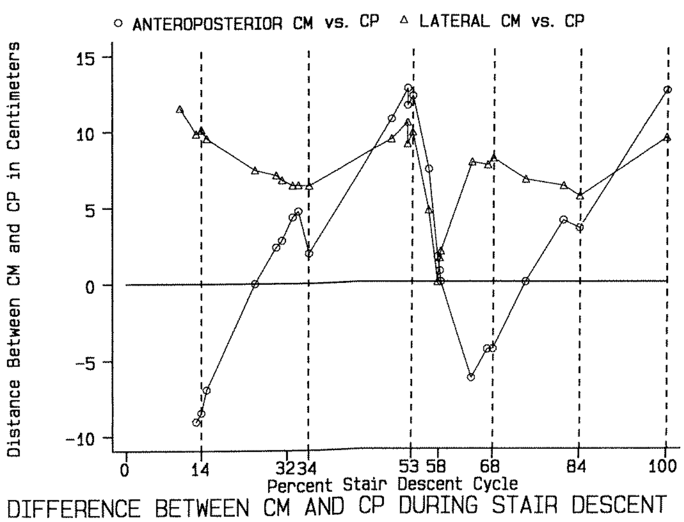

Figure 12.
Difference Between CM and CP During Stair Descent. The distance between the CM and CP in the frontal and sagittal planes is graphed. Because of limitations imposed by the viewing volume computations were limited for the first 10 to 14% of the cycle; therefore, no values are presented. Points indicated on the graph are data.

reaching the first of two maximums at the start of single limb support (14% SD cycle) (**Figure 13**). Vertical GRF gradually decreases until mid stance (32% SD cycle). After mid stance, vertical GRF increases, reaching the second of two maximums at approximately the same time as the initiation of the second double support phase (53% SD cycle). Lateral GRF increases throughout double support, from foot contact until the start of single limb support. Like vertical GRF, lateral GRF gradually declines until mid stance. After mid stance, the lateral GRF increases, reaching its second maximum at the initiation of the second double support phase. A/P GRF demonstrates maximal anterior shear, during weight acceptance, just prior to the start of single limb support (13% SD cycle). Just prior to single limb support, posterior shear forces are apparent. Maximum posterior shear is attained just prior to the double support phase (53% SD cycle).

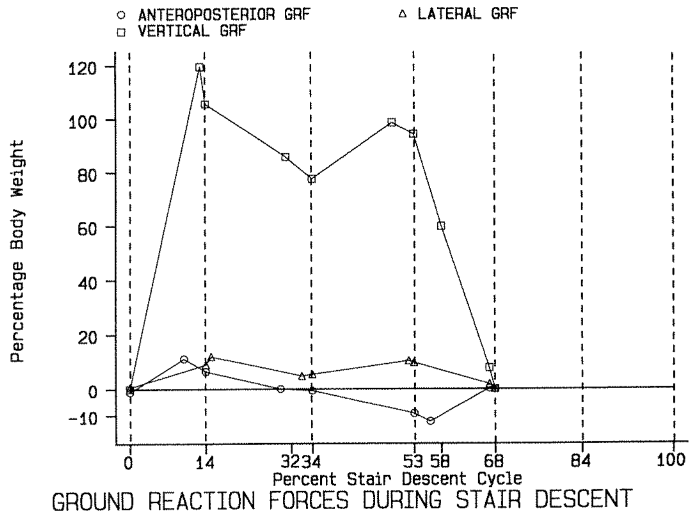

Figure 13.
Ground Reaction Forces During Stair Descent. GRFs during stair descent as a percentage of body weight are graphed. Points indicated on the graph are data.

DISCUSSION

These data supplement the SA and SD phases originally described by McFayden and Winter (9), by using two force plates in conjunction with whole body CM analysis in all three planes. The portions of stance phase in which double support and single support occur are detailed. Single limb support accounts for 31% in SA and 39% in SD cycles; double support accounts for 34% and 29%, respectively. Thus, it is clear that SA commands greater stability among these normal subjects, as evidenced by SA's longer double support and shorter single limb support phases.

In both SA and SD, the CM undergoes a cyclic vertical translation. Vertical translation occurs during approximately 70% of SA and 64% of SD; vertical position maintenance occurs during 30% and 36% of SA and SD, respectively. The CM moves laterally in a cyclic sinusoidal pattern and of roughly the same magnitude as ambulation on level surfaces, for both SA and SD (1,2,3).

Divergence, or the largest separation between CM and CP, signifies positional instability. As expected, the largest lateral divergence is demonstrated either at the initiation of single limb stance (17% SA cycle) or just prior to it (14% SD cycle). In mid stance, the CM and CP converge as the CM passes toward the swinging limb in preparation for weight transfer to, and foot contact of, the swing limb, in both SA and SD. Convergence is maximal during mid double support (59% SA and SD cycles). Maximum divergence between CP and CM occurs twice during the stance phase of gait just as in SA and SD. Convergence between CM and CP signifies positional (static) stability (11,13). As expected, convergence occurs in both the lateral and anteroposterior directions during the middle of double support. Because the CM-CP separation magnitude is greater in SD than SA, it is clear that SD is a more dynamic process. Although any separation of CM-CP during locomotion while under control of an individual may be described as a "controlled fall," the "controlled fall" exhibited during SD demonstrates greater inherent instability because of SD's greater CM-CP separation magnitude in comparison with SA. Krebs et al. (12) and Craik et al. (14) also suggest that stair descent requires more "balance" compensation. Our data suggest that subjects have greater CM-CP separation and shorter double support phases in SD than SA. This suggests that SD is a challenging locomotor task, which may explain in part why so many falls occur on stairs (15).

The subjects who participated in this study were allowed to self-select their velocity of SA and SD. It is unknown exactly what effect a change in velocity would have on the kinematics of SA and SD. It has been demonstrated that the kinematics, kinetics, and electromyographic activity associated with gait are directly related to velocity (16). The effect of varying the velocity of SA and SD is a question for future study. We have attempted to develop a model by which more questions may be asked and answered. Suggestions for future research concern not only the change in kinematics due to changes in velocity but also the effects of age, vestibular problems, or other types of pathology which may affect the ability of the individual to ascend or descend stairs in a safe and independent manner.

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