Kinematic Analysis of Head and Trunk Movements of Young Adults while Climbing Stairs or a Ramp

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Purpose: The purpose of this study was to investigate the kinematic adaptation of head and trunk to ascend stairs and a ramp. Subjects were healthy young adults. Three-dimensional kinematic patterns of head and trunk movements were examined during stair climbing and steeper ramp climbing.

Methods: Fourteen young subjects with no history of chronic or acute musculoskeletal, cardiovascular or respiratory disorders took part in this experiment. Kinematic data were collected using a 6 camera Vicon system (Oxford Metrix, Oxford, England). Repeated measures ANOVA analyses were used to investigate the effect of gait mode on kinematics of the head and trunk.

Results: The angle of the trunk while ascending stairs or a ramp was modified in three human planes ($p<0.05$). The angle of head and neck during the ascending of stairs or a ramp was not changed in the sagittal plane but was changed in the frontal and transverse planes ($p<0.05$).

Conclusion: This study describes and discusses some basic kinematic mechanisms underlying the pattern of head and trunk changes during stair and ramp climbing and showed that postural adaptation of the head and trunk is necessary to maintain balance.

Keywords: Head, Trunk, Kinematics, Stairs, Ramp

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I. Introduction

The human pattern of locomotion has been shown to be highly adaptable to different environments such as stair climbing, changes in walking speed, or slope.[1-3] Ascending and descending stairs or a slope are common forms of locomotion that are required for performing normal activities of daily living such as shopping, using public transportation, or simply getting around in a multistory home or building.

Although we encounter stairs or a ramp regularly, and walking on stairs or a slope has been recognized as an activity that is highly associated with falls in the elderly,[4] very little research has been directed towards the examination of how human walking patterns are modified in such circumstances, particularly the transitions between level ground, stairs and a slope.[5-7] Also, the difference among the three gait modes of locomotion may be significant for the elderly and a patient population. The fact that the elderly and patients have adequate muscle strength and joint ROM for level walking does not ensure that they will be able to walk up and down stairs or a slope. Previous studies[3,8] have shown that gait adaptation on inclined surfaces is achieved by changing the pattern of lower limb motions and modifying the level of activation of the relevant flexor and extensor muscles.

However, how the trunk assists lower limbs in the process of adaptation to stair and inclined walking has not been addressed. Balance during gait may be described as the ability to maintain a relationship between the body center of mass trajectory and the base of support. Abnormal trunk posture may create instability by altering this relationship.[9] So, the control of the pelvis and trunk is important to achieve smooth movement and maintain body equilibrium during gait.[10] During walking, the pelvis and trunk move in the three anatomical planes, and three dimensional analyses reveal very complex patterns of motions between pelvis and trunk.[11] Most of all, the stabilization of the trunk remains essentially in dynamic balance during normal walking. Trunk angular sway has been indicated as a reliable measure of balance stability.[12,13] The trunk slightly inclines forward in faster walking. Rotation of the trunk is slight and occurs primarily in a direction opposite to the direction of pelvic rotation. As the pelvis rotates forward with the swinging lower extremity, the thorax on the opposite side rotates forward as well. This trunk motion helps to prevent excess body motion and to counterbalance rotation of the pelvis.[14] Stokes[11] in a study of treadmill walking found that movements and interactions of the trunk and pelvis were important along with anterior and posterior pelvic tilting, lateral pelvic tilting, and rotation.

Abnormal head and trunk alignment can contribute to a deformity of the body and a decline in the quality of life. Takahashi et al[15] reported that a trunk deformity group, which consisted of individuals with kyphosis, lumbar flatback, and greater than normal lumbar lordosis, tended to score lower on healthiness and life satisfaction measures. Balzini et al[16] reported a similar decline in quality of life in a group of 60 elderly women with trunk flexed posture and lower back pain, and found that subjects with moderate and severe trunk-flexed posture had significantly greater back pain than patients with mild trunk-flexed posture. Therefore, the main purpose of this study was to investigate the kinematic adaptation in healthy young adults of head and trunk to ascending stairs or a ramp. Three-dimensional kinematic patterns of the head and trunk were examined during climbing of stairs and steeper slopes.

II. Methods

1. Subjects

Fourteen healthy subjects (males: 8, females: 6) participated in this study. All were free of musculo-skeletal and neurological dysfunctions. The average age of subjects was 28.13 years (8.69); weight was 66.46 kg (10.82); height was 168.48 cm (13.65); leg length 86.12 cm (5.38); knee width 10.02 cm (1.45); ankle width 8.22 cm (1.84). Each subject signed an informed consent document before the experiment.

2. Data collection

Kinematic data were collected using a 6 camera Vicon system (Oxford Metrix, Oxford, England) and sampled at 100 Hz to capture spatial positions of markers placed on the subject in a plug-in gait full body marker set. Markers were placed on the feet, shanks, thighs, pelvis, trunk, head and upper and lower arms. Data processing was done using designated vicon polygon software. All subjects were instructed to walk barefoot at a self-selected pace on a walkway with stairs, slope or level ground. We made the wood stairs (height: 18 cm, tread: 28 cm, pitch: 30°)[17] and slope (length: 3 m, width: 1.8 m) with the same inclinations to better compare them. Subjects were asked to walk on level ground, stairs or slope in random order. The walking trials were performed repeatedly for a total of three times. Gait cycle was defined as the interval between two sequential initial floor contacts of the same limb.[18,19] Kinematic data were ensemble averaged for each participant across 3 walking trials. Prior to ensemble averaging, individual data was normalized with respect to time of the 0∼100% gait cycle. In this study, we measured the joint angle of head and thorax and spine (lumbar) at heel contact, midstance, toe off and in midswing during walking on a level, on stairs or on a slope.[20]

3. Data analysis

Repeated measures ANOVA analyses were used to investigate the effect of gait mode on kinematics of the head and trunk. All statistical analyses were performed using SPSS ver. 17.0 and p-values less than 0.05 were used to identify significant differences.

III. Results

Figure 1 illustrates changes in head and trunk in the sagittal, frontal, and transverse planes during walking with different gait modes. Head and trunk showed generally similar patterns of adaptation during walking under different gait conditions. But some angles of the head and trunk in each gait phase was different in different gait modes.

1. Sagittal plane

The kinematic patterns of head and neck observed during walking with different gait modes were not modified, but

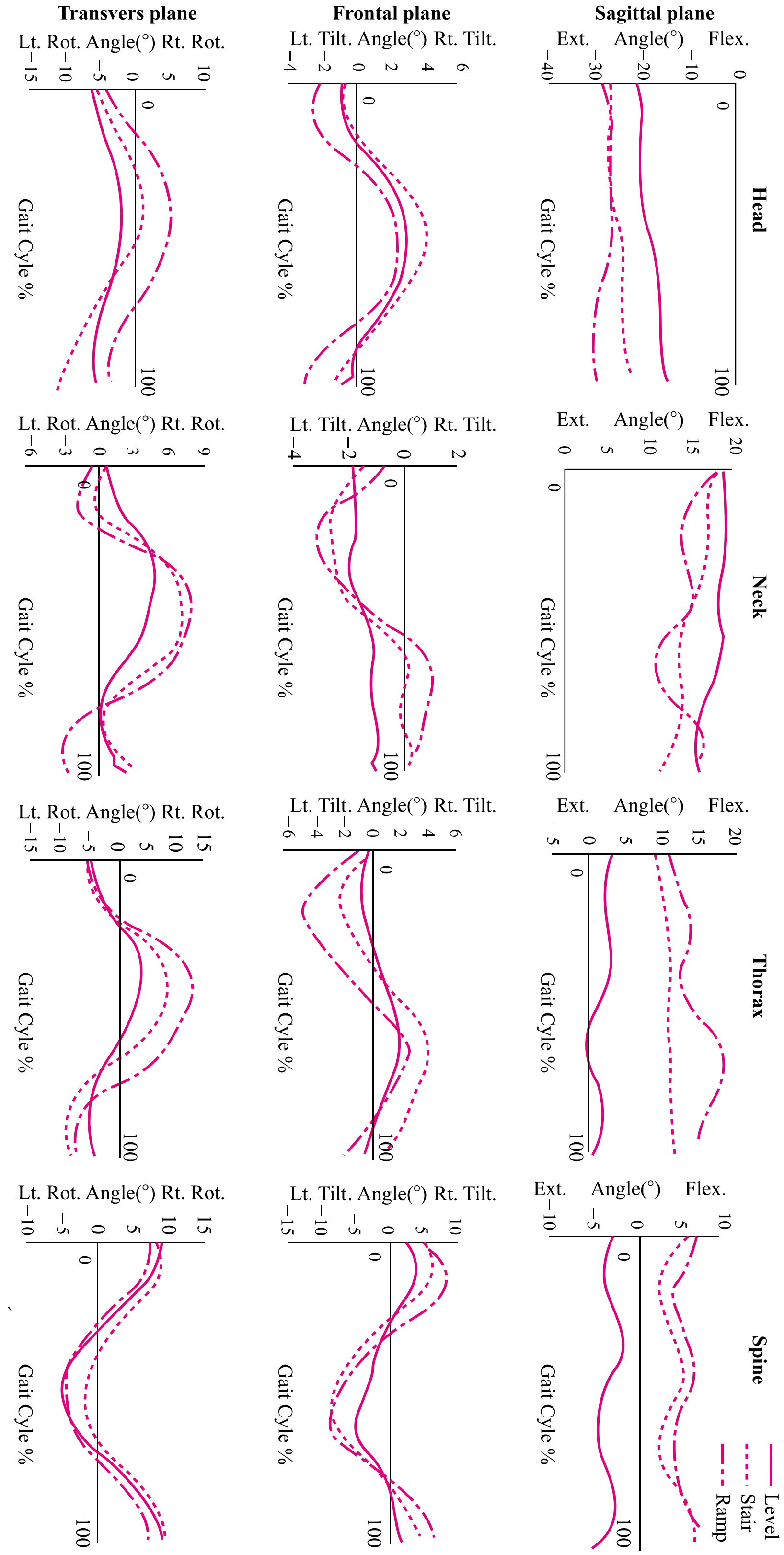

Figure 1. Representation of the joint kinematics of head and trunk during stairs and ramp ascent with different gait mode.

patterns of thorax and spine were modified (Figure 1). In each gait phase, the extension of head and flexion of neck was not significant different with different gait modes ($p>0.05$). However, flexion of the thorax in each gait phase increased during stair and ramp ascending relative to level walking, and significant differences were found between the flexionof the thorax in level walking, stair climbing and ramp ascending ($p<0.05$)(Table 1). Maximum flexion of the thorax in midswing, in particular, increased during ramp ascension. Flexion of the spine in each gait phase also increased during stair and ramp ascending compared to level walking. Significant differences were found for flexion of the spine in different gait modes ($p<0.05$)(Table 1).

2. Frontal plane

The results obtained from the frontal plane for head and thorax and spine during walking with different gait modes were not modified, but results for head and neck revealed some variations (Figure 1). In each gait phase, the tilt of the head and neck was generally not significantly different with gait modes ($p>0.05$), but the tilt of head was significantly different between level walking and ramp walking at heel strike. In addition, the maximum tilt of the thorax increased on the opposite side during ramp ascending, similar to the patterndurin level walking and stair ascending at midstance. Significant differences were found among the maximum tilt of the thorax for level walking and stair and ramp ascending ($p<0.05$)(Table 2). In heel strike, the tilt of spine increased during stair ascending as it had during level walking and ramp ascending and a significant difference was found between level walking and stair ascending ($p<0.05$)(Table 2). In midstance, the tilt of spine increased during ramp ascending as it did during level walking and stair ascending and significant differences were found between level walking and ramp ascending and between stair ascending and ramp ascending ($p<0.05$)(Table 2). In toe off, the tilt of spine increased on the opposite side during stair and ramp ascending as it had during level walking, and significant differences were found between level walking and stair ascending and between level walking and ramp ascending ($p<0.05$)(Table 2).

3. Transverse plane

The kinematic patterns of spine observed during walking with different gait modes were not modified, but that of head and neck and thorax were modified (Figure 1). In midstance, toe off, and midswing, right rotation of the head increased during stair and ramp ascending as during level walking, and significant

Table 1. The results of repeated ANOVA on angle of head and trunk during ascending with different gait modes in the sagittal plane (mean±SD) (Unit: °)

Regions	Gait phase	Level	Stair	Ramp	F	p
Head	Ext. Heel Strike	-21.06±11.66	-27.29±13.58	-28.48±12.57	2.95	0.07
	Max. Ext. Midstance	-20.32±12.73	-27.32±15.86	-26.80±14.60	1.84	0.20
	Ext. Toe Off	-17.59±13.43	-24.14±17.12	-27.01±15.60	2.40	0.11
	Max. Ext. Midswing	-16.36±14.15	-24.53±15.06	-30.57±15.54	2.81	0.10
Neck	Flex. Heel Strike	18.53±10.79	17.91±10.31	17.78±11.02	0.04	0.96
	Max. Flex. Midstance	18.87±11.52	16.71±11.05	13.59±9.67	1.23	0.33
	Flex. Toe Off	18.35±12.25	13.36±14.08	11.10±12.77	1.96	0.16
	Max. Flex. Midswing	16.24±13.18	13.70±13.16	13.22±12.40	0.24	0.79
Thorax	Flex. Heel Strike	3.21±4.28	9.21±7.09*	10.93±7.07†	19.41	0.00
	Max. Flex. Midstance	2.16±4.68	10.31±9.03*	13.36±7.85†	25.97	0.00
	Flex. Toe Off	1.39±4.34	10.70±8.03*	13.52±7.51†	33.42	0.00
	Max. Flex. Midswing	0.98±4.29	10.93±7.28*	17.62±7.28†‡	59.00	0.00
Spine	Flex. Heel Strike	-2.98±7.62	5.62±9.46*	6.59±11.30†	24.50	0.00
	Max. Flex. Midstance	-3.54±8.44	2.47±10.34*	4.25±9.93†	18.16	0.00
	Flex. Toe Off	-3.71±8.07	4.78±11.62*	5.91±9.00†	23.26	0.00
	Max. Flex. Midswing	-3.16±7.63	3.65±9.88*	4.74±9.44†	20.35	0.00

*significant difference between level and stair, †significant difference between level and ramp, ‡significant difference between stair and ramp

Table 2. The results of repeated ANOVA on angle of head and trunk during ascending with different gait mode in frontal plane (mean±SD) (Unit: °)

Regions	Gait phase	Level	Stair	Ramp	F	p
Head	Tilt. Heel Strike	-0.94±4.43	-0.82±5.41	-2.29±4.43†‡	4.38	0.02
	Max. Tilt. Midstance	-0.20±4.52	0.03±5.26	-1.92±4.94	2.06	0.17
	Tilt. Toe Off	2.85±5.33	3.77±4.50	2.31±5.55	1.64	0.24
	Max. Tilt. Midswing	1.31±4.98	1.66±5.10	0.27±6.50	0.80	0.47
Neck	Tilt. Heel Strike	-1.85±2.93	-1.45±2.72	-0.72±2.59	2.84	0.08
	Max. Tilt. Midstance	-1.69±2.46	-2.69±2.73	-3.03±2.83	2.14	0.14
	Tilt. Toe Off	-1.06±3.49	-0.25±3.05	0.38±4.04	3.10	0.08
	Max. Tilt. Midswing	-1.13±3.63	-0.08±3.08	0.92±3.45	2.68	0.11
Thorax	Tilt. Heel Strike	-0.48±2.18	-0.32±3.35	-1.11±3.10	0.72	0.50
	Max. Tilt. Midstance	-0.86±2.40	-2.39±3.89	-5.19±4.37†‡	15.44	0.00
	Tilt. Toe Off	1.84±1.86	3.43±2.88	1.64±4.90	3.37	0.07
	Max. Tilt. Midswing	1.04±2.09	3.14±3.23	1.43±4.39	2.92	0.07
Spine	Tilt. Heel Strike	2.21±4.07	5.17±5.87*	5.04±5.60	3.98	0.03
	Max. Tilt. Midstance	2.49±3.66	3.75±4.53	7.03±6.30†‡	4.95	0.03
	Tilt. Toe Off	-5.24±2.775	-8.95±4.68*	-9.47±4.62†	11.61	0.00
	Max. Tilt. Midswing	-1.26±3.38	-1.63±5.66	-1.09±8.99	0.05	0.95

*significant difference between level and stair, †significant difference between level and ramp, ‡significant difference between stair and ramp

differences were found among the gait modes (p<0.05)(Table 3). In midstance, right rotation of the neck increased on the opposite side during ramp ascending as during level walking and stair ascending, and significant differences were found between level walking and ramp ascending (p<0.05)(Table 3). In toe off, the right rotation of the neck increased during stair and ramp ascending as during level walking, and significant differences were found between level walking and stair ascending and between level walking and ramp ascending (p<0.05)(Table 3). In toe off, the right rotationof the thorax increased during stair and ramp ascending as during level walking, and significant differences were found among gait modes (p<0.05)(Table 3). In midswing, the right rotation of thorax increased during ramp ascending as during level walking and stair ascending, and significant differences were found between level walking and ramp ascending and between stair and ramp ascending (p<0.05)(Table 3).

IV. Discussion

In normal walking, the body functionally divides itself into two units, a passenger unit (head, neck, trunk and arms) and a locomotor unit (two lower limbs and pelvis). While there is motion and muscle action occurring in each, there is a difference between the two units. The passenger unit is responsible only for its own postural integrity, while the locomotor unit is a major determinant for muscle action within the locomotor system.[21] Therefore, the analysis of biomechanical aspects of stair and ramp ascent can add to our understanding of the varied and complicated processes involved in human locomotion and also be useful in the design of private and public environments where stairs and ramps are employed.[22] Stairs and ramp climbing is an especially challenging task compared to level walking. The transition from walking on level ground to ascending stairs or a ramp presents a number of challenges to the locomotor control system, and proprioceptive and visual sensory systems are needed to maintain balance.[23,24] Swing limb trajectories must be modified to ensure safe toe clearance and foot placement as the elevation and orientation of the support surface changes.[6] In fact, the use of slope walking has recently proven advantageous to accessing specific demands of pathological gait in orthopedic and neurological conditions.[3,7] However, many natural and existing urban environments can often exceed such recommendations. A significant decrease in walking speed has been found when walking either up or down a steep ramp of

Table 3. The results of repeated ANOVA on angle of head and trunk during ascending with different gait mode in transverse plane (mean±SD) (Unit: °)

Regions	Gait phase	Level	Stair	Ramp	F	p
Head	Rot. Heel Strike	-6.27±6.90	-5.37±6.82	-4.11±7.09	3.37	0.05
	Max. Rot. Midstance	-3.84±6.76	-1.78±6.85*	1.13±6.61†‡	9.76	0.00
	Rot. Toe Off	-2.66±7.85	-1.34±7.26	3.58±8.39†‡	7.48	0.01
	Max. Rot. Midswing	-5.02±8.54	-6.66±8.58	-1.34±8.9844†‡	7.02	0.00
Neck	Rot. Heel Strike	0.74±6.01	0.637±5.57	-0.73±5.89	1.00	0.38
	Max. Rot. Midstance	2.73±6.30	1.08±6.45	-0.90±5.31†	4.44	0.02
	Rot. Toe Off	3.35±6.58	6.64±5.55*	7.06±7.55†	10.47	0.00
	Max. Rot. Midswing	0.19±6.16	0.81±6.09	0.71±5.37	0.15	0.86
Thorax	Rot. Heel Strike	-5.55±6.78	-5.14±6.73	-5.43±6.86	0.04	0.96
	Max. Rot. Midstance	-0.98±6.53	-1.29±4.76	-0.85±6.94	0.07	0.94
	Rot. Toe Off	4.41±5.93	5.64±5.50*	10.51±6.26†‡	37.88	0.00
	Max. Rot. Midswing	-4.65±5.98	-5.97±5.72	-1.23±6.66†‡	9.99	0.00
Spine	Rot. Heel Strike	8.66±4.22	7.92±3.86	7.14±3.50	1.24	0.31
	Max. Rot. Midstance	4.90±3.59	6.30±3.46	3.82±4.92	1.88	0.17
	Rot. Toe Off	-4.52±3.25	-2.08±4.59	-3.90±3.89	2.93	0.07
	Max. Rot. Midswing	3.34±2.83	4.34±4.18	1.15±7.64	1.50	0.26

*significant difference between level and stair, †significant difference between level and ramp, ‡significant difference between stair and ramp

greater than 9° pitch, while little difference in walking speed has been noted between level ground and lower grade ramps.[6,25] It was hypothesized that walking onto low grade stairs and slopes will involve very similar kinematic patterns to that of level walking and that more significant adaptations will occur at steeper stairs and slopes.

Results from the present study show that the adaptation process also includes modifications in trunk orientation in sagittal and frontal planes.[3,10] The key mechanism when adapting to ascend stairs or a slope is to lift up the swinging leg by performing a simultaneous increase in hip and knee flexion of that limb. We consider that trunk functions during level walking and stairs and slope climbing could be modified following neuromuscular and orthopedic disorders affecting lower limb movements. Leroux et al[10] reported that the main postural requirement when adapting to slope walking is to change trunk orientation in the human plane. Han et al. reported that stairs and ramp climbing used a different muscle recruitment pattern than for level walking.[26] Trunk alignment showed a forward tilt during uphill walking as compared with level walking. The results of our study also showed that the angle of head and trunk during ascending stairs or a ramp was modified in three human planes. The angle of head and neck during ascending stairs and ramp was not changed in the sagittal plane but was changed in frontal and transverse planes. These results suggest that the main strategy was to maintain the center of gravity within the base of support during stair and ramp climbing. So, trunk tilt is necessary to move the center of gravity ahead of the base of support to assist the forward propulsion of the body.[9,10]

These accentuations in head and trunk were all performed to compensate for lower limb changing during ascending stairs or ramps compared to level walking. Compensatory movements from the head and trunk could be even more pronounced and play an important role in the maintenance of balance when locomoting on stairs and ramps in adults with different gait modes.

V. Conclusion

Kinematics of head and trunk are changed in different gait modes in the three human planes. In particular, variations in thorax and spine appeared in all planes while variations in head and neck mainly appeared in frontal and transverse planes. Our results show that gait pattern will be affected by gait mode such as stair and ramp climbing. In summary, this study describes and discusses some basic kinematic mechanisms underlying the pattern of head and trunk movements during climbing stairs and ramps, and shows thatpostural adaptation of the head and trunk is necessary to achieve balance. Knowledge of head and trunk kinematics in different gait modes should be helpful in understanding the appropriate gait patterns in stair and ramp locomotion.

Author Contributions

Research design: Han JT
Acquisition of data: Han JT
Analysis and interpretation of data: Han JT
Drafting of the manuscript: Han JT
Administrative, technical, and material support: Han JT
Research supervision: Han JT

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