Three-dimensional motions of trunk and pelvis during trans-femoral amputee gait

Goujon H.[1], Sapin E.[1], Fodé P.[2], Lavaste F.[1,2]
1: Laboratoire de Biomécanique ENSAM CNRS UMR 8005, Paris, France
2: Centre d'Etude et de Recherche pour l'Appareillage des Handicapés (CERAH), Woippy, France

***Abstract*— Few anterior studies investigated upper body movements of above knee amputees. The aim of the present study is to identify characteristics of upper body kinematics and torque transmission to the ground during locomotion of transfemoral amputee compared with healthy subjects. The influence of clinical factors as age, length of the stump, activity on these characteristics is also investigated. A protocol is developed to record kinematics of trunk and pelvis using an optoelectronic system simultaneously with forces and moments applied by the feet on the ground measured by two force plates. Twenty-seven trans-femoral amputees and a group of thirty-three asymptomatic subjects participate in this study. Angular ranges of motion of scapular and pelvic girdles are calculated in the three planes of space. The relative phase of the motion of these girdles in the horizontal plane is also evaluated. Statistical tests (t-test) are used to compare the amputated population and the sound population and to determine the influential of clinical factors. Angular ranges of motion of upper body are globally increased for the amputees while walking velocity decreases. Specific patterns for above-knee amputees are found for pelvic tilt, pelvic angular velocity in the transverse plane and torques around the vertical axis transmitted by lower limbs. The coordination between pelvic and scapular girdles is altered. Some correlations show the links between parameters, particularly, the coordination is found to be dependant on walking speed. Clinical factors influence this coordination and the mobility of upper part of the body.**

Keywords- amputees, biomechanics, gait, motor skills, kinetics

I. INTRODUCTION

The gait of above-knee amputees is different from the gait of non-disabled people. Particularly, trans-femoral amputees have to adapt to the lack of physiologic knee, which implies coping responses in the entire body. In the literature, many studies on the gait of above-knee amputees focused on kinematic and kinetic changes in the lower limbs [1, 2]. However, previous studies showed the importance of trunk movement in human gait in particular the interaction between pelvis and thorax [3]. The relative phase between pelvic and thoracic transverse rotations was often used [3] in order to quantify the counter-rotation that occurs between the two segments. Besides, the analysis of trunk motion especially in the transverse plane allowed determining specific patterns in pathological gait. Thus, Wagenaar [4] and Van Emmerik [5] both showed a decrease of counter-rotation between pelvis and thorax respectively in hemiplegic and parkinsonian patients. Concerning trans-femoral amputees, few studies investigated upper body motions. Cappozzo [6] analyzed the angular displacements of trunk but his study was limited to four patients. Sjödahl [7] focused on pelvic motion in the frontal and transverse plane before and after special gait re-education but did not study thoracic motion. Tazawa [8] examined 3D pelvic and thoracic movements comparing "good" walkers with "others" among twelve patients. However, he did not analyse the relative motion of the two segments.The aim of the present study was to identify specific 3D patterns of motion for pelvic and scapular girdles during trans-femoral amputee gait thanks to a wide sample of patients. The relationship between pelvic and scapular transverse rotations was also investigated at the same time with the couple transmitted by the lower limbs to the ground. All these parameters were compared with the values observed for asymptomatic people and their sensitivity to several clinical factors were researched.

II. MATERIAL AND METHODS

A. Patients

Twenty-seven patients and thirty-three healthy subjects were included in this study. All had a trans-femoral amputation. Mean age of the amputee group was 50.9 years with a range from 28 to 73 years. The time since amputation was between 4 and 61 years. Five patients had a short stump, five a medium one and the others had a long one. The prosthetic fitting and the medical follow-up of every patient were made in CERAH (Centre d'Etude et de Recherche sur l'Appareillage des Handicapés, Créteil, France). The control group was composed of subjects whose age was included in the range of the group of amputees. The mean age of this group was 44.3 years (28-61 years).

B. Protocol

All experiments took place in the gait laboratory of CERAH. Both kinematic and kinetic data were collected according to the global protocol described by Goujon [9]. Twelve cameras (Vicon® 524, Oxford Metrics Ltd, Oxford, UK) and two force plates (AMTI® Advanced Mechanical Technology, Inc, Massachussetts, OR6-5) were used in the same way as for previous experiments [9]. Patients were asked to walk on a path of nine meters at their self-selected speed. For each patient, data were recorded during at least ten trials.

Activity level was evaluated thanks to a questionnaire fulfilled by medical doctor.

C. Data analysis

Activity of each patient was assessed by a scoring method (maximum score: 24). Ten patients had a poor activity (with a score inferior to 11). To assess the movements of the upper body during gait, we defined two rigid segments: the pelvis and the thorax. Anatomical frames were defined for each segment thanks to skin markers on the pelvis and the scapular girdle. Therefore, in this study, thorax movements were linked to those of scapular girdle.

To calculate 3D motion, we used cardan angles between each segment and the laboratory reference system and between the two segments. We calculated angular velocity of pelvis and thorax relatively to the ground from kinematic data. We defined a spline, corresponding to the evolution of each angle during gait, for each trial. Then, the spline function was drifted to obtain angular velocity at each trial. Finally, the average of angular velocity was evaluated from the previous derivatives.

General parameters allowed evaluating the global efficiency of gait (average walking velocity, step lengths and stance durations).To describe motion of pelvic and thoracic girdles, angular ranges of motion were calculated in the three planes of space for the pelvis, for the scapular girdle and for their relative movement. To characterize the transverse counter-rotation of girdles, we calculated the continuous relative phase following the method described by Van Emmerik [3]. The torque transmitted by lower limbs to the ground characterized dynamic aspect of gait. Using the position of the centre of pressure and the forces and moments given by force plates, the torque around the vertical axis was calculated according to gait cycle on each lower limb during its contact with the floor.

To evaluate the reliability of our method, we carried out a numeric simulation of different sources of error on kinematic measurements. The misplacement of each anatomical landmark was modelled by a constant white noise applied on the coordinates of the landmarks. The range was set to 10 mm for the markers of the pelvis and 5 mm for the markers put on the shoulders. The random error of measure of an isolated marker (0.71 mm) was applied as the standard deviation value of a Gaussian noise set on the coordinates of all markers at each acquisition time during the gait cycle. We repeated 500 times this simulation on a same gait cycle and calculated the difference with the signal of reference. For each parameter, the accuracy was twice the standard deviation value over the 500 iterations.

To identify significant differences between amputated and sound subjects, we used a t-test or a Wilcoxon test depending on whether the parameter was normally distributed or not.

Among the amputee group, we also investigated the influences of the following factors: age, stump length, time since amputation and activity. For each factor, we divided the whole group in subgroups corresponding to the levels of the factor. T-tests or Wilcoxon-test allowed to research statistical differences of parameters between the subgroups.

III. RESULTS.

A. Accuracy

The total uncertainty, obtained calculating twice the deviation standard value of each parameter on 500 iterations, was reduced to 0.6° for the ranges of motion of the pelvis and 1.2° for the ranges of motion of the trunk. The accuracy of relative continuous phase was 11.4°.

B. Comparison between amputee and sound groups

The results concerning general parameters showed that the gait of trans-femoral amputated patients was globally altered. Walking velocity was significantly inferior and the symmetry of step length and stance phase duration was broken (table 1). In the same time, pelvic and thoracic kinematics of the amputated persons were different from the one of sound subjects. Angular ranges of motion were significantly higher in the sagittal and frontal planes for the pelvis and in the three planes for the thorax (table 1). On the opposite, pelvic transverse range of motion was equivalent for the two groups. Likely, the range of motion of relative movement between pelvis and thorax did not increased for the disabled people as well in the frontal plane as in the horizontal plane (table 1). Nevertheless, the relative phase between the tranverse movements of pelvic and scapular girdles was significantly reduced for this group (table 1). Thus, asymptomatic subjects showed a globally out-of-phase movement (with a mean relative phase of 120°) of the pelvis relatively to the thorax although this movement was in-phase (mean relative phase of 79°) for the amputee group.

Figure 1 and 2 put in relief the specific patterns of pelvic motion exhibited by amputated people. The first curve (figure 1) represents the comparison of pelvic tilt between the amputee and the sound groups. It can be noticed that the pattern of motion was completely different for the amputees. Pelvic tilt occurred toward the stance side during the single limb part of the stance. On the opposite, asymptomatic subjects tilted their pelvis toward the swinging side during the phase of double limb support.

In the transverse plane, whereas pelvic rotation angle was similar for the two groups, the evolution of pelvic angular velocity during gait was different for amputated people as shown in figure 2. First, the maximal angular velocities were reached latter during the stance phases for amputated people just before the heel contact both at sound and amputated contact. On the contrary, these maxima occurred during single limb support for non-disabled people. Secondly, although the curve was absolutely symmetrical for sound people, angular velocity evolution varied for amputated persons according to the stance side. When the stance took place on the amputated side, the velocity remained near to zero during 20 % of the cycle while it waved when the stance occurred over the sound side like for non-disabled people.

Kinetic particular pattern during above-knee amputee gait can be seen on figure 3. The figure compares torques transmitted through the lower limbs to the ground around the vertical axis of the laboratory expressed at the centre of pressure for the 2 groups. Evolution pattern for the amputated patients was very different for the amputated side. On the sound side, the pattern was similar with sound people pattern.

TABLE I. COMPARISON BETWEEN SOUND SUBJECTS AND AMPUTATED PATIENTS – FOR EACH PARAMETER : MEAN (STD) - * : PARAMETER NORMALLY DISTRIBUTED – P-VALUE : T-TEST FOR NORMALLY DISTRIBUTED PARAMETERS, WILCOXON TEST FOR OTHERS PARAMETERS

Parameters	***Amputees***	***Control group***	***p-value***
Walking velocity* (m/s)	1.0 (0.2)	1.2 (0.2)	<0.01
Sound step length (m)	0.68 (0.06)	0.7 (0.09)	
Amputated step length (m)	0.65 (0.07)	0.71 (0.06)	<0.01
Sound stance phase duration (% cycle)	65 (4)	59 (2)	<0.01
Amputated stance phase duration (% cycle)	57 (2)	59 (2)	<0.01
ROM pelvis in sagittal plane(°)	8 (5)	4 (1)	<0.01
ROM pelvis in frontal plane * (°)	10 (3)	8 (3)	<0.01
ROM pelvis in horizontal plane * (°)	11 (5)	13 (4)	<0.01
ROM thorax in sagittal plane (°)	7 (3)	4 (2)	<0.01
ROM thorax in frontal plane (°)	9 (3)	5 (2)	<0.01
ROM thorax in horizontal plane (°)	12 (4)	9 (3)	<0.01
ROM of relative motion between pelvis and thorax in frontal plane*(°)	12 (4)	13 (4)	
ROM of relative motion between pelvis and thorax in horizontal plane*(°)	13 (5)	16 (5)	
Relative phase of transverse motion of pelvic and scapular girdle *(°)	79 (14)	120 (35)	<0.01

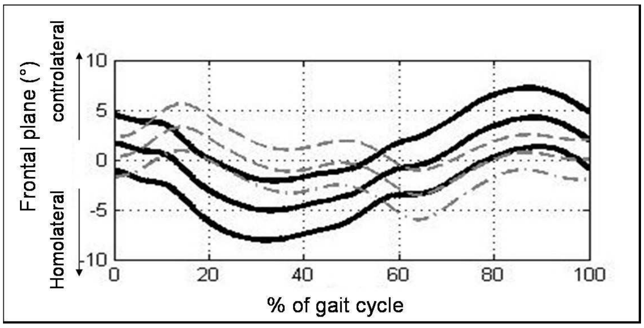

Figure 1. Mean curves (+/-1 std) of pelvic tilt in the frontal plane (in °) for the sound group (in grey dash lines) and the amputee group (in black solid lines)

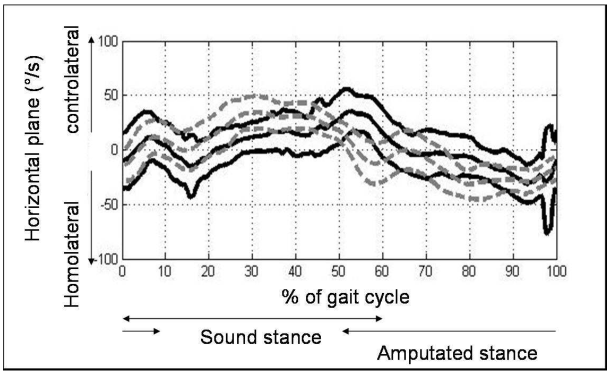

Figure 2. Mean curve of pelvic angular velocity in the transverse plane (in °/s) for the amputee group (in black solid line) compared with the corridor (mean +/- 1 std) of asymptomatic subjects (in grey dashed lines)

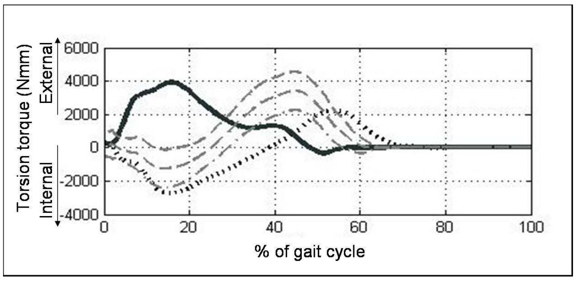

Figure 3. Mean curves for amputee group (in black lines) of the torque applied by lower limb at centre of pressure around the vertical axis (in Nmm) for amputated side (solid line) and sound side (dot line) compared with the corridor (mean +/- 1 std) of sound subjects (in grey dashed lines)

C. Influence of clinical factors

Statistical tests allowed analysing the dependency of several parameters to clinical factors among the group of amputees. Walking velocity highly (p=0.0018) depended on level of activity. For patients with low activity, walking velocity was lower (mean: 0.9 m/s) than for patients with normal rate of activity (mean: 1.1 m/s). The pelvic range of motion in the frontal plane was also sensitive to several factors. Total pelvic tilt was different (p=0.02) for elderly (mean: 12°) than for middle-aged patients (mean: 9°). This range of motion was more important (p=0.01) for less active subjects (mean: 9°) than for normally active people (mean: 12°). Stump length influenced total pelvic range of motion in the sagittal and frontal planes. Thus, patients with short stump had their sum of range of motion in these two planes (mean: 24°) higher (p=0.04) than patients with long stump (mean: 18°). Finally, the relative phase calculated between transverse motion of pelvic and scapular movement was mainly influenced by three factors. Elderly patients walk with a more in-phase movement (mean relative phase: 69°) than younger patients (mean relative phase: 87°) (p=0.03). Patients who had been amputated a long time ago had a significantly (p=0.04) smaller relative phase (mean 73°) than patients whose time since amputation was average (mean: 85°).

IV. DISCUSSION

This study aimed at identifying kinematic characteristics of upper body motion for trans-femoral amputees.

Trunk kinematics, especially coordination between pelvis and thorax, were often reported in healthy subjects [3] or to characterize the gait of pathological subjects [4, 5]. But, in trans-femoral amputated people, only a few studies were about upper body kinematics [6-8]. These works were lead on small samples of patients. Cappozzo [6] compared angular displacements of the upper body for four amputees with five referent subjects. Tazawa [8] did not used a healthy population as a reference but compared two groups of amputees, among twelve patients, according to a subjective classification of the quality of gait. More recently, the study of Sjödahl [7] established a comparison between eighteen non-disabled subjects and twelve above-knee amputated patients concerning pelvic motion. On the opposite, the present work relied on a population of twenty-seven transfemoral patients and thirty-three sound subjects. Moreover, whereas some studies focused only on the transverse plane [4, 5], we completely investigated kinematics of trunk and pelvis and their coordination according to the three planes of space. Finally, our work brought an insight in the transmission of torque to the ground. Neither previous studies presented patterns of the torque along the vertical axis applied to the ground by trans-femoral amputees.

The findings in the present study confirm that gait is globally altered for amputated patients. In particular, walking velocity was lower for amputated people but was closer to the speed of normal subjects when patients were active. This is consistent with the results of Sjödahl's study [7] in which re-education resulted in an increase in walking velocity.

The angular ranges of motion of pelvis and thorax were larger for amputees, which was observed earlier by Cappozzo comparing four amputated and five normal men [6]. In the frontal plane, the pattern of movement was completely specific for amputees. This pattern was already presented by Cappozzo [6] and Sjödahl [7] on smaller samples of patients. Our study shows that this pattern is a characteristic of above-knee amputee gait. The fall of the pelvis on the side of the stance leg can be explained by the weakness of stump abductors that are not strong enough to stabilize the pelvis [6, 7]. This is supported by the significant difference of total motion of the pelvis in the sagittal and frontal planes within the group of amputees between patients with short and long stumps. Jaegers [10] pointed out that the hip stabilizing muscles become more atrophied with increasing level of amputation. As a result, the pelvis of the amputees with short stump is more mobile in the sagittal and frontal planes. It has been found that frontal pelvic range of motion is also higher for elderly and less active amputated subjects. We think that it can be explained by an amyotrophy that occurs with age or a lack of activity.

The pattern of transverse rotation of the pelvis was very close for sound and amputated people. However, there was a specific pattern of angular velocity in this plane with a lower value during mid-stance. Looking at Sjödahl's curves [7], an increase of this angular velocity can be observed after re-education.

The continuous relative phase was significantly lower for amputated than for asymptomatic subjects. A decrease of this phase was also observed for stroke patients [4] and for parkinsonian patients [5]. This in-phase pattern compared to the out-of-phase pattern of sound subjects is attributed to an increase in axial stiffness of the trunk linked to the pathology [4] or to a protective guarding behaviour [11]. Selles [11] suggested that the reduction of comfortable speed observed in patients with low back pain would be a consequence of the inability to counter-rotate thorax and pelvis. This could explain the lower walking velocity of amputated patients compared to non-disabled people. A significant difference of phase pattern was found between elderly and young patients. Contrary to this finding, Van Emmerik [5] did not found any age effects on the relative phase. Even so, a dependency of relative phase to age would confirm a link with the axial stiffness of the trunk that ought to increase with age. Time since amputation had an influence on the relative phase for amputees. Wagenaar [4] suggested that re-education should improve counter-rotation of pelvis and thorax for stroke patients. Our findings tend to confirm this point as patients, amputated a long time ago, did often not profit by an adapted re-education.

Concerning kinetic results, we could think that huge differences observed between sound and amputated subjects are due to a modification of upper body angular accelerations. The analysis of the pattern of the torque showed that torque transmitted through the prosthesis was modified in comparison with torque transmitted through the sound limb. Further investigation would research a correlation with trunk dynamic.

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REFERENCES

1. Sjödahl, C., Jarnlo, G.-B., Söderberg, B. and Persson, B.M., Kinematic and kinetic gait analysis in the sagittal plane of trans-femoral amputees before and after special gait re-education. Prosthet. Orthot. Int., 2002. 26(2): p. 101-112.
2. Jaegers, S.M.H.J., Arendzen, J.H. and de Jongh, H.J., Prosthetic gait of unilateral transfemoral amputees : a kinematic study. Arch. Phys. Med. Rehabil., 1995. 76(8): p. 736-43.
3. Van Emmerik, R.E.A. and Wagenaar, R.C., Effects of walking velocity on relative phase dynamics in the trunk in human walking. Journal of Biomechanics, 1996. 29(9): p. 1175-1184.
4. Wagenaar, R.C. and Beek, W.J., Hemiplegic gait : akinematic analysis using walkig speed as a basis. J Biomech, 1992. 25(9): p. 1007-1015.
5. Van Emmerik, R.E.A., Wagenaar, R.C., Winogrodzka, A. and Wolters, E.C., Identification of axial rigidity during locomotion in parkinson disease,. Archives of Physical Medicine and Rehabilitation, 1999. 80(2): p. 186-191.
6. Cappozzo, A., Figura, F., Gazzani, F., Leo, T. and Marchetti, M., Angular displacements in the upper body of AK amputees during level walking. Prosthetics and Orthotics International, 1982. 6: p. 131-138.
7. Sjödahl, C., Jarnlo, G.B., Söderberg, B. and Persson, B.M., Pelvic motion in trans-femoral amputees in the frontal and transverse plane before and after special gait re-education. Prosthetics and Orthotics International, 2003. 27: p. 227-237.
8. Tazawa, E., Analysis of torso movement of trans-femoral amputees during level walking. Prosthetics and Orthotics International, 1997. 21: p. 129-140.
9. Goujon, H., Bonnet, X., Sautreuil, P., Maurisset, M., Darmon, L., Fode, P., et al., A functional evaluation of prosthetic foot kinematics during lower-limb amputee gait. Prosthetics and Orthotics International. in press.
10. Jaegers, S.M.H.J., Arendzen, J.H. and de Jongh, H.J., An electromyographic study of the hip muscles of transfemoral amputees in walking. Clinical Orthopaedics and Related Research, 1996. 328: p. 119-128.
11. Selles, R.W., Wagenaar, R.C., Smit, T.H. and Wuisman, P.I.J.M., Disorders in trunk rotation during walking in patients with low back pain: a dynamical systems approach. Clinical Biomechanics, 2001. 16(3): p. 175-181.