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Analysis of torso movement of trans-femoral amputees during level walking

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Abstract

The purpose of this study is to analyze the movement of unilateral trans-femoral amputees' gait and find patterns of compensated movement to accommodate the loss of locomotor power on one side. A 3-D analyzer system and force plate were used to measure 12 amputees.

The main focus was to find characterized movement particularly of the upper body such as pelvis, shoulder and arms. It was Saunders *et al.* (1953), who said that the human body can be purposely divided into two subsystems in analyzing man's locomotion.

This study, however is not to measure the level of function, but to evaluate the appearance of gait.

Twelve markers were placed on the subjects, and two locations for measuring points were used to measure movement of the torso in three axis (X, Y, Z) without measuring the position of the centre of gravity. The two points were at shoulder level, and at pelvic level.

Lissajou's figure was used to evaluate the movements at these two marks. The quality of the gait was determined through subjective evaluation by the author. Determination was made on two factors, one from observing the gait of the amputees and the other, patterns from their Lissajou's figure of two measuring points.

Then they were categorized as good walker or "other". Good walkers had results at shoulder level which were closer to the symmetrical Lissajou's figure of normal walkers. Yet the symmetrical pattern was not present at the pelvis level for the good walker.

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Introduction

Over the past decade there have been many developments in prosthetic components which aimed for ever higher levels of function. The most important functional loss in the trans-femoral amputee is the knee mechanism.

There are high performance knees, energy storing feet, new materials, new socket designs, with the result that with these advanced aids for amputees, they can now run and participate in many sports activities. Amputees are able to run 100 metre sprints, but the trans-femoral amputee's gait is still noticeable among normal people due to their upper body movements.

This study is to identify the characteristics of trans-femoral amputee's movements, particularly the upper body movements. The belief is that trans-femoral amputees have their own characteristic gait pattern just as patients with knee flexion contracture or fixed ankle joint have their own gait pattern.

Much research has been done on comparison between amputees and non-amputees. In this study, the goal is to find the gait pattern of trans-femoral amputees and compare this pattern between the good walkers and the "other" walkers.

The reason for the two measuring points, instead of using the usual centre of gravity, is twofold; firstly, the difficulty of finding the centre of gravity for amputees with prostheses, and secondly, the need to find the actual movement between pelvis and shoulder as well as the entire torso. This is due to the fact that the author holds the strong opinion that amputees can never walk in the way that normal walkers can. An amputee must compensate with movement to overcome the different locomotive ability between sound leg and prosthetic leg.

Method

Equipment

A 3-dimensional Analyzer (Oxford Metrics, Vicon system 370) with 6 CCD cameras was used to measure coordinates on the subjects. The subjects wore 12 markers on their body, 6 on the left side, and 6 on the right side.

A force plate (Kyouwa Dengyou EPP-386AS) was incorporated but used only to measure the timing of the gait cycle and to identify the stance/swing phase to exact scale.

The first task of this measurement was to create conditions which would gather accurate data of the subjects' gait within a space of 2 metres (X-axis) x 2 metres (Y-axis) x1.8 metres (Z-axis), with a total length of 8 metres, including an initial 4 metres to allow the amputees to get into a steady gait, with 2 metres of walk through area after the actual measuring space, so that amputees can maintain speed while walking through the measuring space.

It was necessary to have this set up in order to reproduce as closely as possible; the usual gait pattern of the subjects.

Subjects and conditions

The selection of amputees was random, and conditions were as follows:

1. subjects must be using trans-femoral prostheses;
2. prosthetic knee mechanism must not have locked knee;
3. must have endo-skeletal prosthesis;
4. must have foam cover attached;
5. no restriction on socket design;
6. must be using most comfortable heel height for the subject;
7. must be able to walk with confidence at the most comfortable speed;
8. subjects' arms were allowed to have free swing;
9. the prostheses were in the normal alignment configuration as used by the amputees.

There was no previous adjustment on any of the prostheses before the measurements were taken. And there was no restriction on age, sex, weight, height or length of stump.

It should be pointed out that no bilateral amputees were used in this study.

Marker positions

1. left and right acromion process.
2. left and right lateral epicondyle.
3. left and right styloid process.
4. left and right iliac crest.
5. left and right outside of knee joint.
6. left and right lateral maleoli.

A total of twelve coordinates were used.

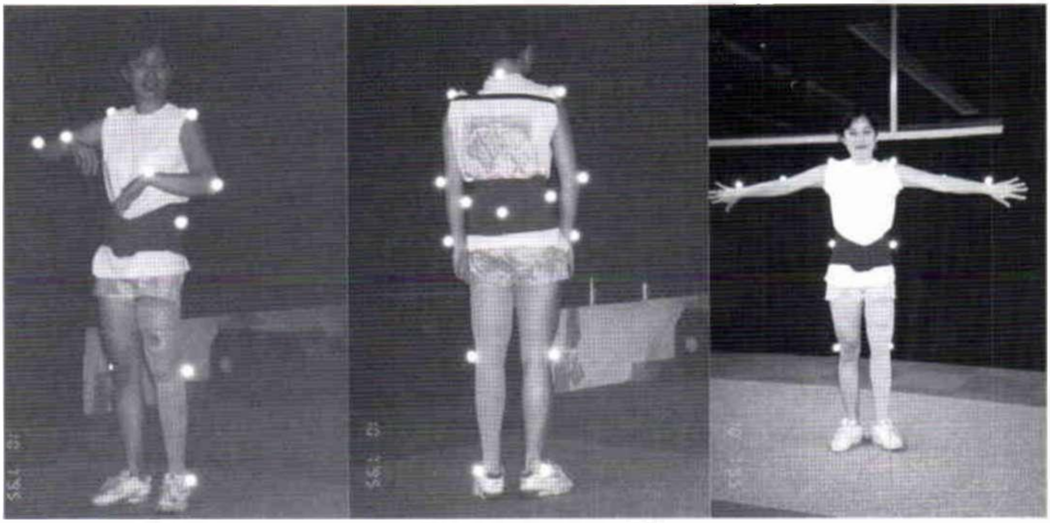

Fig. 1. Subject with markers.

Walking conditions

Twelve spherical markers, 15mm in diameter, were attached to each subject's body at the points described above with double-sided tape (Fig. 1).

Subjects were given free selection of gait speed, and they started walking 4 metres behind the measuring space. The only instruction given to the subjects was to place the right foot on the right force plate and vice versa for the left one.

This simple instruction was given to minimize interference in reproducing their usual gait, since it is rather difficult to require their trans-femoral amputees to walk along a straight line due to lack of lateral support with their prostheses.

No metronome, no step length, step width, no specific side (L or R) for entering the force plate was used so as to make amputees relaxed during the measurement period.

The first measurement was taken in the static upright position for zero calibration, and three measurements were taken at a speed chosen by the amputees.

Data treatment

A Vicon system calibrated all coordinates into a 3-dimensional matrix within the measuring space.

A 3-dimensional diagram established the centre of the measuring space as the origin of measurement, and the direction of X axis is set left to right against line of progression, Y axis is on the line of progression and Z axis is perpendicular to the floor (Fig. 2).

A 3-dimensional diagram provides sequential data, and the sampling frequency for this study was done at 60Hz, with the measuring time 4 seconds. This means that each marker will produce 240 sequential data. The data were processed by a digital low pass filter as Bryant (1984) described.

According to Cappozzo (1981) the appropriate cut-off frequency is 6Hz, and 6Hz was the figure used in this study.

Calibration

Based on smoothed sequential data, calibration was done on angular and linear relationship between the acromia and iliac crests.

Calibration was based on the observation made from behind the subjects in the frontal plane, so the starting points were set at the left acromion process and the left iliac crest.

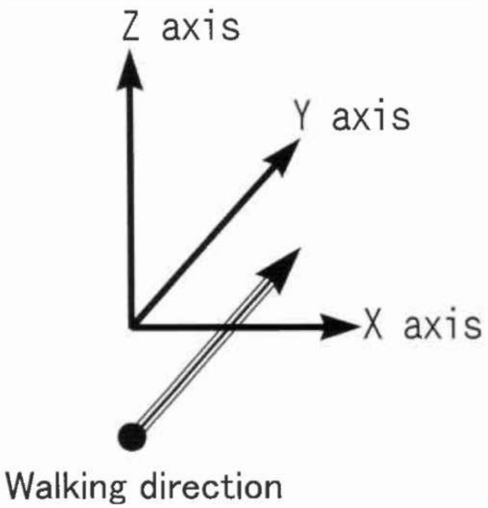

Fig. 2. Three axis of dimension.

If the left acromion process matrix is set as (X_1, Y_1, Z_1) at a given time, and at the same instance the right acromion matrix is set as (X_2, Y_2, Z_2), then the angle Θ of the line between these two can be calculated as follows:

$\Theta = \arctan (Z_2-Z_1) / (X_2-X_1)$

Referencing of the markers location on the body was established using data from the standing still position (Fig. 3).

Angulation at pelvic level was done by the same calculation.

Lissajou's figure

A Lissajou's figure was made on the mid-point between both acromion processes and iliac crests.

Often, the direction of movement of the subjects and the Y axis of the measuring space are not exactly the same, and this causes shifting of the locus on each gait cycle.

The presumption was made that subjects move from point A to point B in a straight line, and the centre is selected from the time of heel contact during gait cycle.

The coordinate of first heel contact is (X_1, Y_1, Z_1), the coordinate of the second heel contact is (X_2, Y_2, Z_2), and from this, the amount of shifting by the subject in the measuring space will be (X_2-X_1).

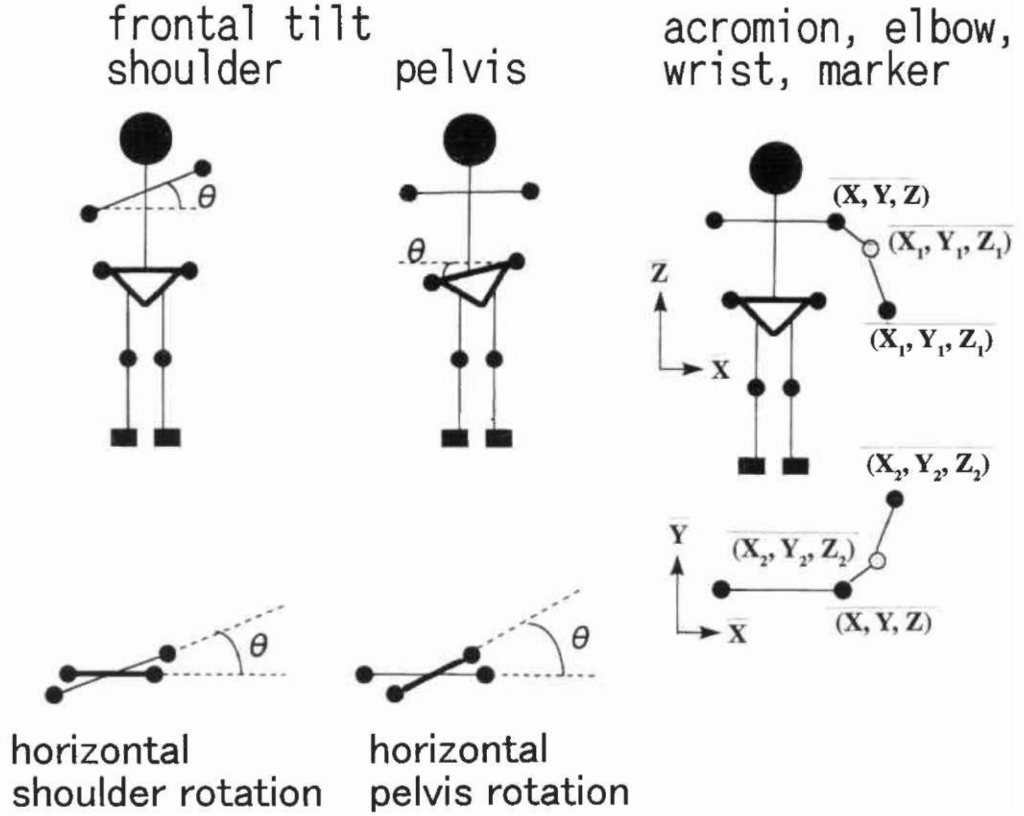

Fig. 3. Calculation of angle.

Results and discussion

The concept of "Locomotor and Passenger" was applied to this study of evaluating the gait of trans-femoral amputees. Instead of comparing the trans-femoral amputees' gait with normal gait, in this study the focus was on identifying the movement characteristics of trans-femoral amputees to compensate for their loss of locomotor system. It also, compares the good walker and "other" walker within trans-femoral amputees.

Twelve subjects were arranged in order according to the appearance of their gait. Also, evaluation of the movement of cross-over points at shoulder and pelvis level, using Lissajou's figure, was done. These two subjective evaluations had the same result.

Twelve subjectively evaluated Lissajou's figures are shown in Figures 4.1, 4.2, 4.3. From these two separate subjective evaluations, 5 (numbers 1-5) were categorized as good walkers and 7 (numbers 6-12) were classified as "others". They were numbered in order from the best to worst walkers and, these numbers were used in all graphs and material.

The walking speed of the 12 subjects was measured, but the order of their speed did not necessarily correspond to whom were the best or the worst walkers, as can be seen in Figure 5.

Lissajou's figure in frontal plane

The mid-point between the acromia and the iliac crests not only represents movement at one point, but also the movement at two points, therefore, movement at both distal parts can be measured.

This mid-point method indicates that the accuracy of measured data is very close to the method of one point measuring usually used in Lissajou's figure. But the method used in this study is also able to pick up movement in the lateral part of the body.

In this study, all the data is compared with the sound side and the amputated side, in contrast to the usual method in the Lissajou's figure of using the left and right sides. To compare the

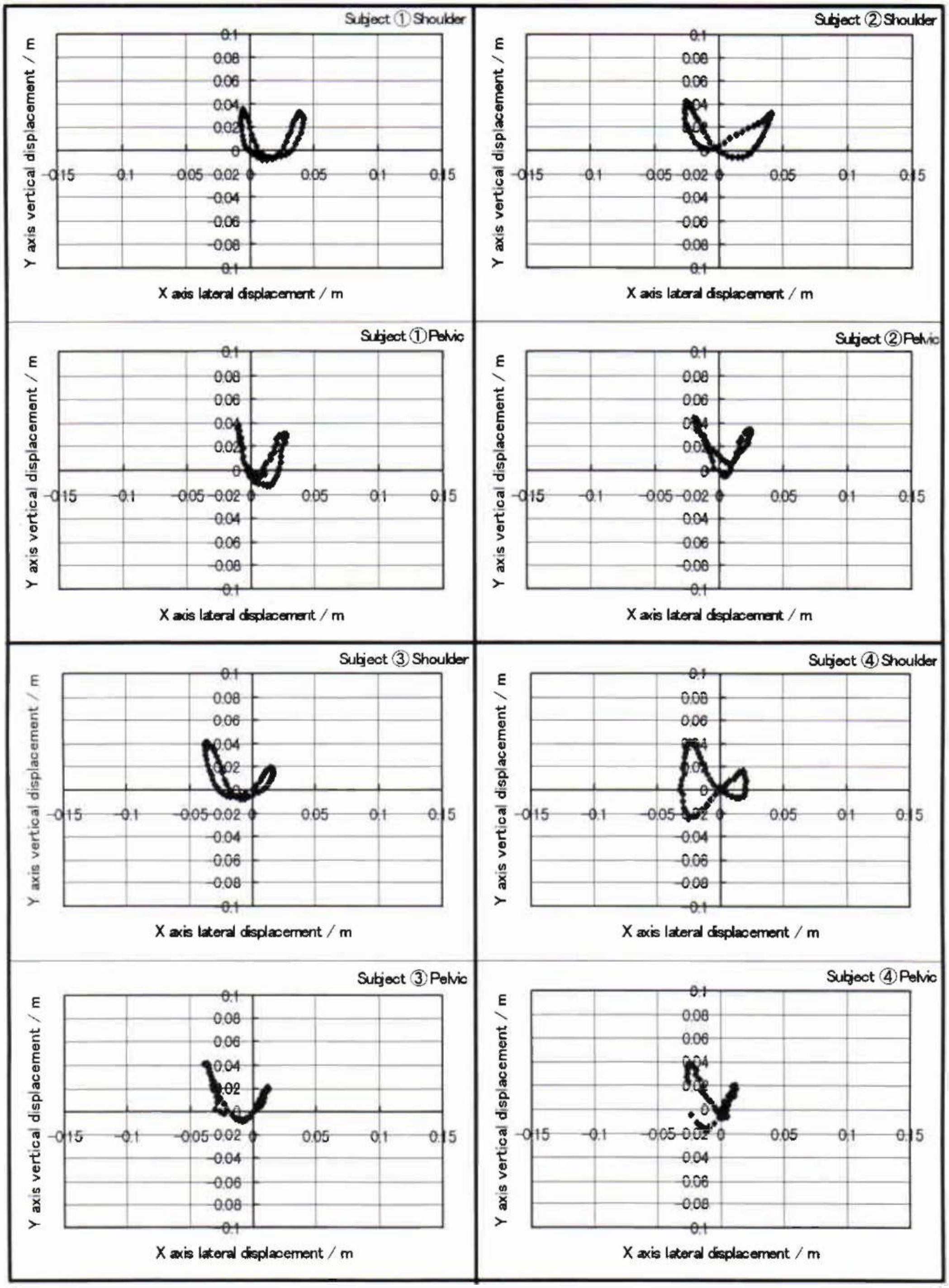

Fig. 4.1. Lissajou's figure.

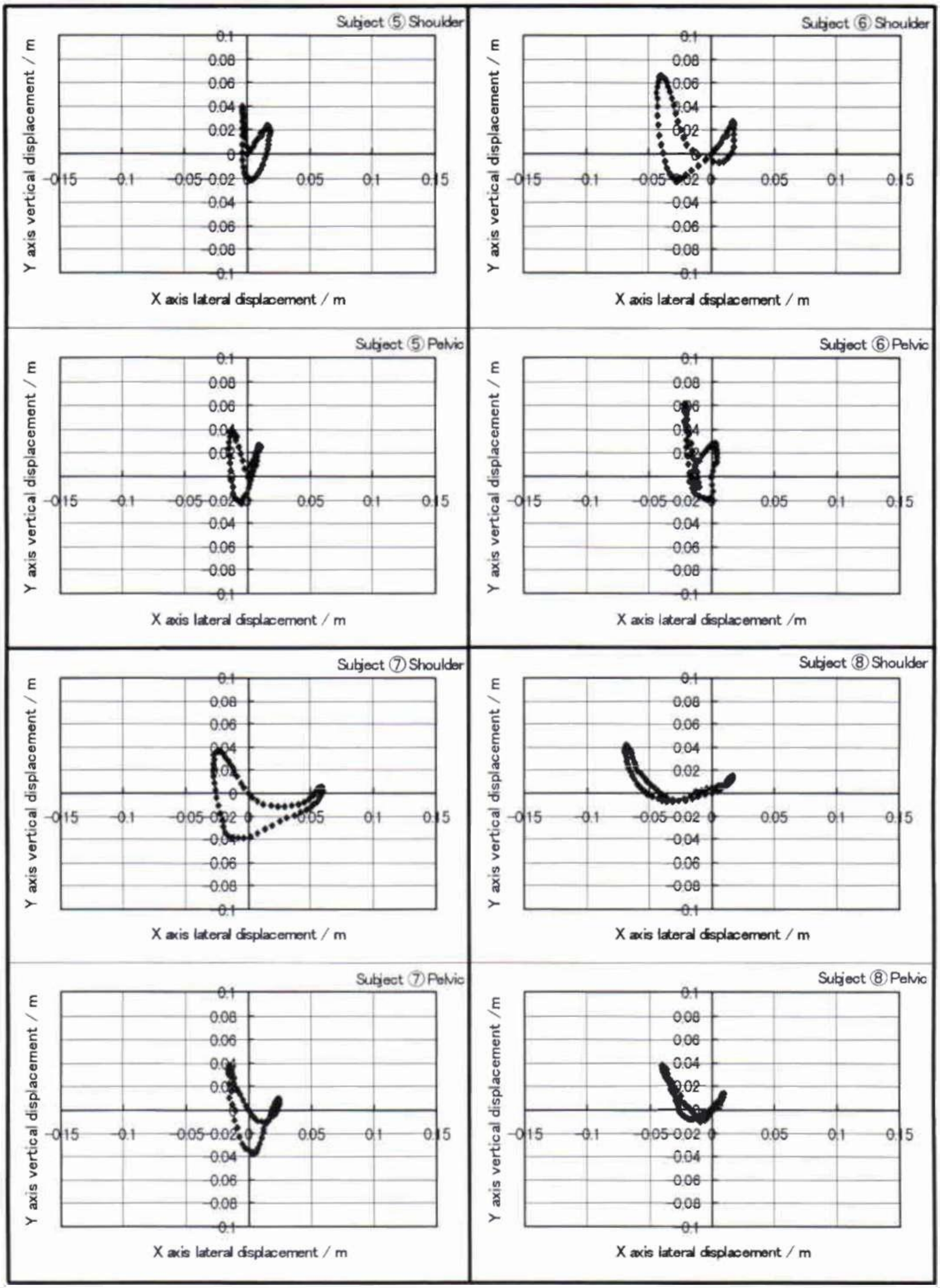

Fig. 4.2. Lissajou's figure.

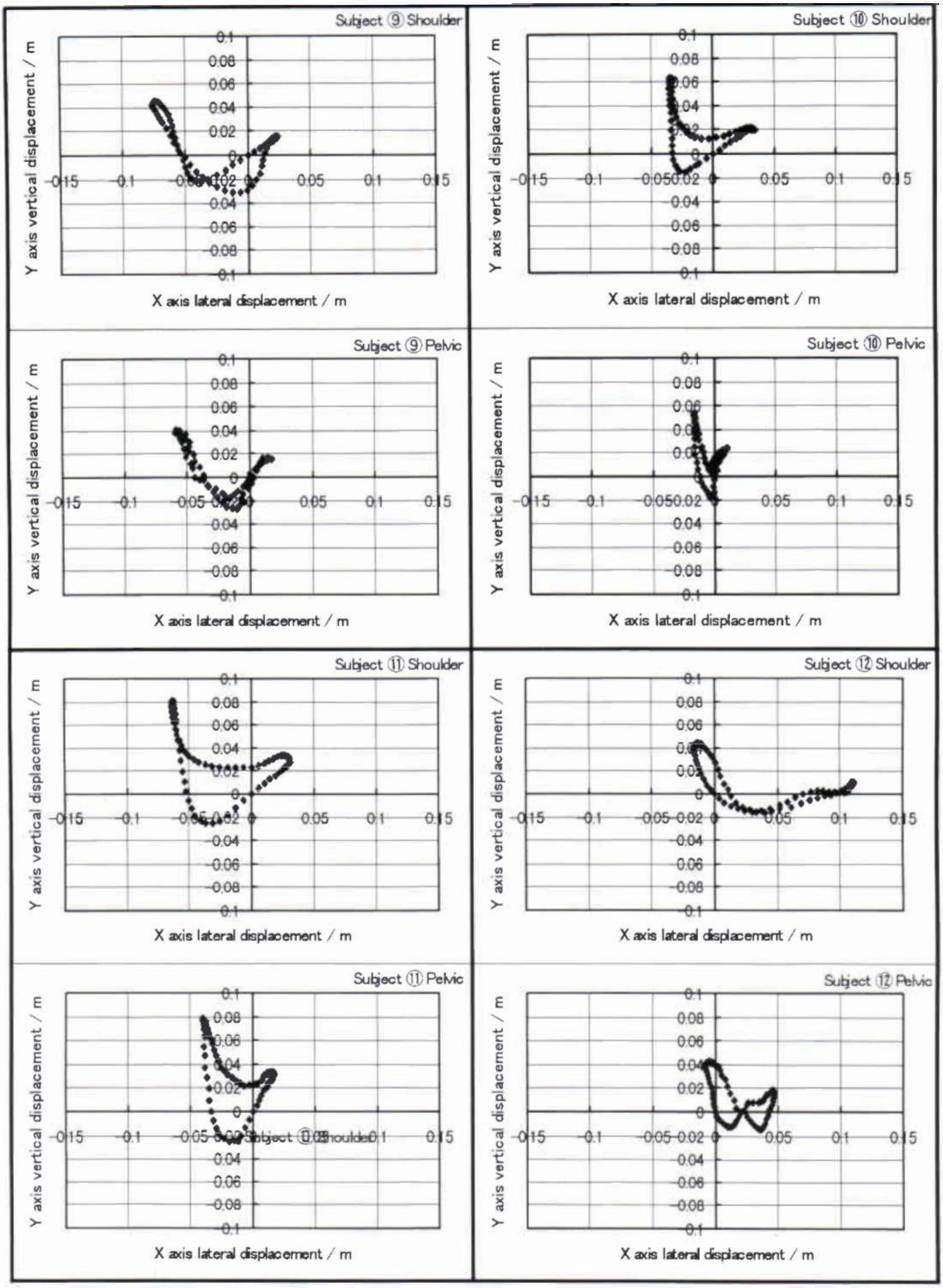

Fig. 4.3. Lissajou's figure.

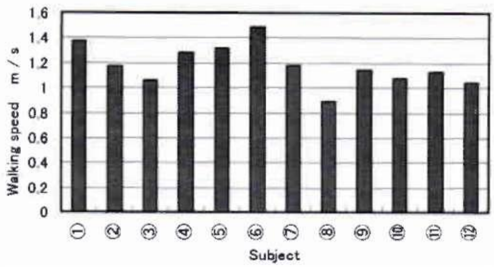

Fig. 5. Walking speed of subject.

data more easily, it has been shown with the sound side on the right and the amputated side on the left.

It is surprising that the results from the two subjective evaluations were exactly the same. All subject's names were deleted.

In the Lissajou's figures, 7 subjects showed bigger displacements.

Shoulder level

The most noticeable point of body movement is at the shoulder level, and the amount of maximum movement on Lissajou's figure was measured in the vertical plane and lateral horizontal plane.

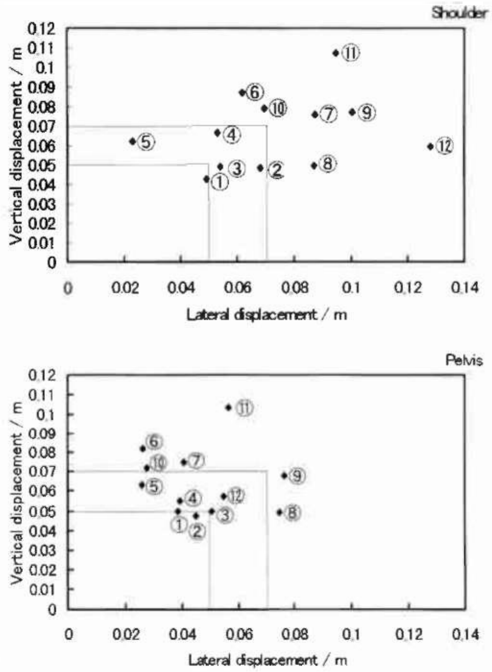

Fig. 6. Frontal plane lateral displacement I.

Figure 6 indicates maximum movements at shoulder level in two planes of all 12 subjects. The X-axis shows lateral maximum displacements and the Y-axis indicates maximum vertical displacement of the shoulder measuring point, which is mid-point between both acromion process markers.

There was only one subject within the 5cm area, but there were 5 subjects within a 7cm area, and 5 of those were the very same 5 subjects chosen as good walkers in the subjective evaluation.

Pelvic level

Using the same method as with the shoulder, there were 6 subjects in the 7cm area, and 5 of those were from the group of good walkers, and one was in the 5cm and 7cm area respectively, but from the "other" group (Fig. 6).

In this graph, X-axis indicates lateral displacements and Y-axis indicates vertical displacements.

Total amount of displacements at shoulder and pelvic level

The next comparison was the total amount of both lateral and horizontal displacement at pelvic and shoulder level (Fig.7).

A 14cm area was chosen and 6 subjects were within that area, but all the good walkers were within the 12cm area. The next closest one was nearer the 14cm line.

Differences in the amount of movement between shoulder and pelvic levels

Another comparison was done with Lissajou's figure which indicated the differences in movement between shoulder and pelvis (Fig. 7). This was a case of the pelvis being the locomotor and the shoulder the passenger.

Hypothetically, a perfectly normal walker will have his/her zero points at both X and Y axis.

The largest difference in vertical plane between shoulder and pelvis was 1.1cm and the smallest one was 0.03cm and both were from the group of good walkers.

On the other hand, lateral displacement resulted in a more dramatic figure. The largest lateral displacement between shoulder and pelvis was 7.7cm and this was in the "other" group.

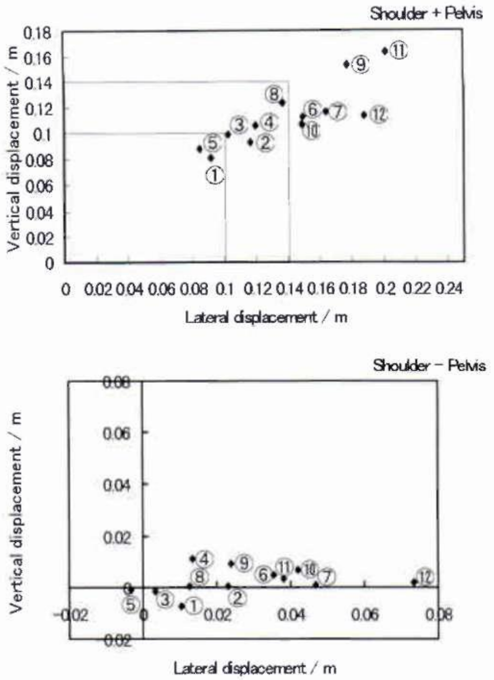

Fig. 7. Frontal plane lateral displacement II.

The smallest displacement was 0.3cm and was from the good walker group. All the good walkers were within 2.2cm lateral displacement.

Results from Lissajou's figure make it clear that the subjects chosen by the subjective evaluation left smaller displacement figures in all aspects. The one exception, subject No. 12, which appears in the good walker group in test 2, was worst in test 4 with the largest lateral displacement of 7.3cm.

Shoulder and pelvic tilt in frontal plane

These angles were calibrated from lines made from two points at shoulder and pelvic level.

Calibration was based on the observation made from behind the subjects in the frontal plane, so the starting points were set at the left acromion process and the left iliac crest.

Tilting angle at shoulder level

Figure 8 shows the maximum tilting angle at shoulder level in the frontal plane. The prosthetic side is on the right and the sound side is indicated on the left.

Even though angulations were different for subjects Nos 3, 5 and 8, the study shows that they always walk with their sound side shoulder higher than the other. Subject No. 10 indicated the opposite by having his/her prosthetic side higher all the time. It is obvious that there is a clear pattern between the good walkers and "others". Also, there was similarity in the symmetrical movement and degree of angle in the different subjects.

Tilting angle at pelvic level

Figure 9 shows the result of pelvic tilt in the frontal plane, with the right side prosthetic and the left side sound. This graph shows a pattern between the two groups; the good walkers' angle of tilt is smaller, whereas all those from the "other" group are bigger.

These two pieces of data provide evidence that good walkers are able to stabilize their pelvis during the stance phase on either leg. In other words, they are able to keep their pelvis in the right position during the swing phase of both legs.

From these results, it is quite safe to assume that good walkers can maintain the pelvis level. It is evident that good walkers either have sufficiently strong lever arm strength in their amputated hip joints or they engage in compensatory movements in the pelvis, or in a higher region of the trunk as well, such as the

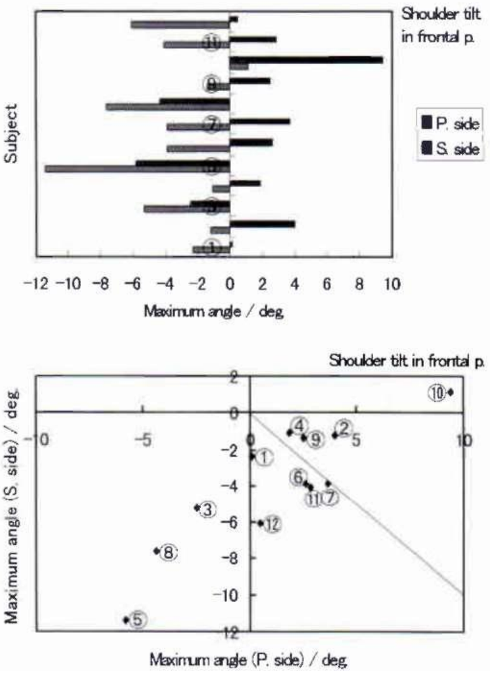

Fig. 8. Shoulder tilt in frontal plane.

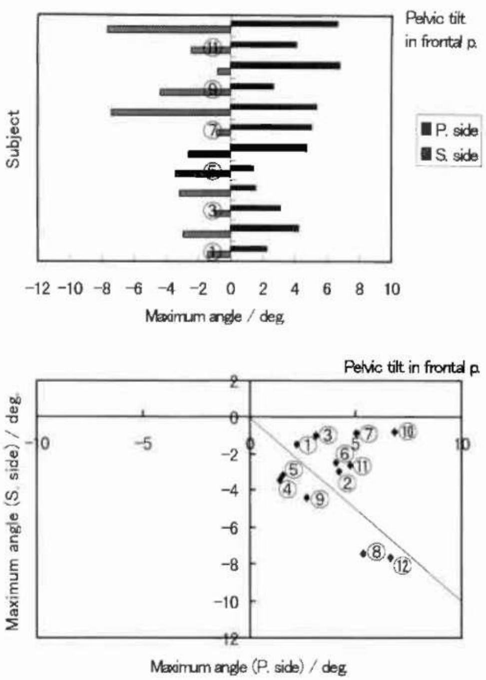

Fig. 9. Pelvis tilt in frontal plane.

shoulder. This cannot, however, be supported by the data here.

Rotation in horizontal plane

Calibration was based on observation made from behind the subjects in the frontal plane, so zero points are set at the left acromion process, and the left iliac crest.

The figures calibrated to compare the rotation in the horizontal plane need to have very careful attention.

Inman *et al.* (1981) stated that 8 degrees of rotation occurs during one gait cycle, 4 degrees of rotation each to anterior and to posterior from the mid-point. Also, on one leg there must be 8 degrees of rotation between pelvis and the foot, which is planted on the ground.

This means that the trans-femoral amputee must have rotation between the socket and pelvis, unless the prosthesis is equipped with a torque reducing unit.

Relative factors between tilt angle and horizontal rotation regarding shoulder and pelvis both have serious meaning. For the trans-femoral amputee particularly having rotation between the socket and stump is a very serious matter. For those reasons, this chapter is a key section of this study.

Horizontal rotation at shoulder level

Figure 10 shows the shoulder rotation of the 12 subjects. The good walkers had lesser degrees of movement and their movement was much more symmetrical.

In general, symmetry was evident for the "others" as well, except for subjects Nos. 5 and 10.

Horizontal rotation at pelvic level

It is quite clear that the good walker group has a pattern that can be observed in Figure 11.

The good walker group had a common pelvic movement, in that their prosthetic side pelvis never moved behind the pelvis of the sound side during an entire gait.

The "other" walkers' sound side pelvis tended to move somewhat forward of the prosthetic one.

From these points, it can be assumed that there is less movement between the prosthetic side pelvis and the prosthesis, especially in the good walker.

Also, good walkers turn more on their sound side pelvic rotation, but very little on their prosthetic side pelvic rotation.

Comparing total movement of the trunk, it is quite obvious that good walkers move their

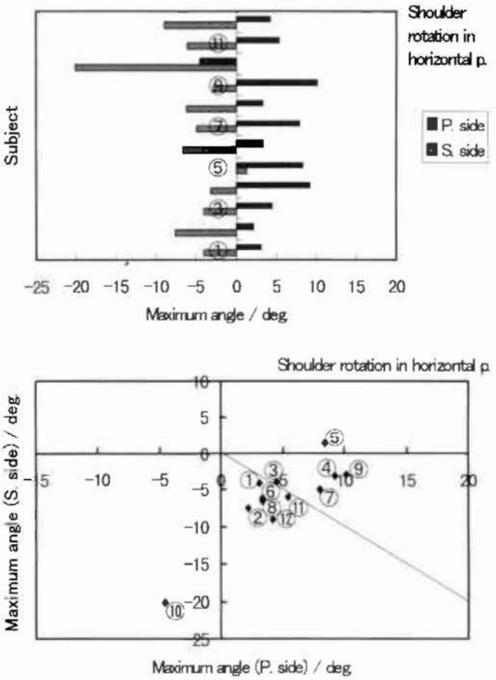

Fig. 10. Shoulder rotation in horizontal plane.

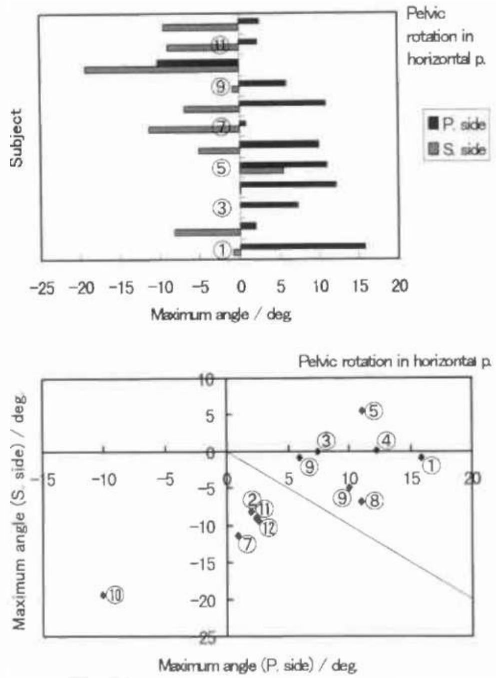

Fig. 11. Pelvis rotation in horizontal plane.

shoulders in a very symmetrical way, yet they move their pelvis rather lopsidedly, and this is one of the compensatory movements to overcome their disability with locomotion.

Step length and arm swing length

Legs and arms are a counterbalancing movement through the trunk. This is a very normal attitude in human locomotion.

When lower locomotion has unequal strength or movement, it will naturally have an effect on the arm swing movement.

Step length

Figure 12 the step length chart, shows the length of the prosthetic step on the Y-axis and the sound side step length on X-axis.

There is no pattern nor difference between good walkers and the "others". In spite of uneven locomotor strength, it is clear that trans-femoral amputees can stride the same with either the prosthetic or sound leg.

Arm swing length

Figure 13 is a graph showing arm swing length measured from the acromion process to the styloid process on the sagittal plane. This

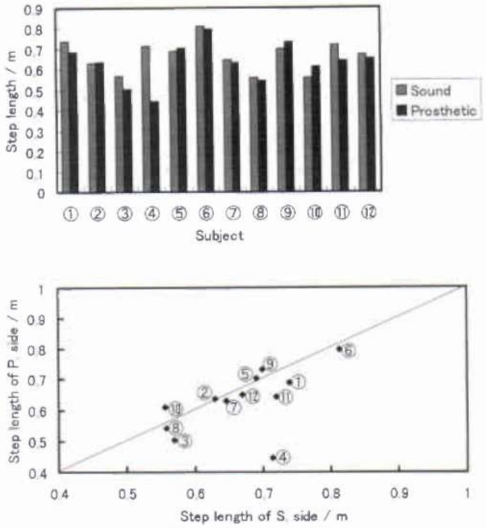

Fig. 12. Step length.

measurement did not include abduction, or adduction and did not consider elbow flexion.

Every subject in this study showed that the swing of the prosthetic side arm was larger and it moved further forward to the body.

There was no pattern and no difference between the good walkers and the "others".

The sound side arm swing was smaller for all the subjects.

Conclusion

Present prostheses have no power of their own. Their locomotive function is basically a

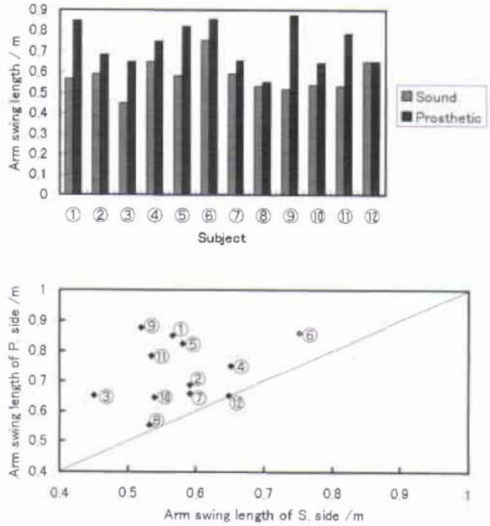

Fig. 13. Arm swing.

pendulum movement. Amputees move their stump to swing the prosthesis, which is mainly controlled by a knee mechanism.

With different locomotive abilities in their lower limbs amputees have to make compensatory movements to overcome their disabilities.

Through this study, a few points have been clarified in this regard.

Amputees who walk well have lesser movement in their gait, and most noticeable is their shoulder lateral displacement.

But, good walkers have rather lopsided pelvic movements, and it can be assumed that they are making compensatory movements.

Of particular interest, is that good walkers keep their pelvic horizontal rotation in relation to the prosthesis much smaller compared to the sound side pelvic horizontal rotation.

This has the result that, between pelvis and shoulder, there is uneven rotation between sound side and amputated side.

It was rather difficult to evaluate the data on the movement of arms due to the complex movement of shoulders (adduction, abduction), and elbow (flexion, extension). But it was clear that arm swing is a balancing factor to accommodate weakness of push-off on the prosthetic side.

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The Forchheimer Prize

The Forchheimer Prize has been established by the Forchheimer family to honour the memory of Sylvia and Alfred Forchheimer. It is awarded every three years at the World Congress and will next be presented at the Closing Ceremony of the 9th World Congress, Amsterdam on Friday July 3 1998.

The Prize will be awarded for the most outstanding paper on Objective Clinical Assessment, Clinical Evaluation or Clinical Measurement published in *Prosthetics and Orthotics International* during the three years prior to the Congress.

The President and Executive Board of the International Society for Prosthetics and Orthotics and the Forchheimer family reserve the right to withhold the Prize should no suitable paper be published.