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Biomechanical significance of the correct length of lower limb prostheses: a clinical and radiological study.

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Abstract

The length of the lower limb prosthesis was compared with the length of the contralateral lower extremity in 113 Finnish war-disabled amputees by a radiological weight bearing method developed by the author. Considering a shortening of 10 mm for above-knee prostheses and of 5 mm for below-knee prostheses as tolerance limits, the length of the prosthesis was acceptable only in 17 cases (15% of the total group). In 79 cases (70%) the prosthesis was up to 47 mm too short and in 17 cases (15%) up to 40 mm too long. Chronic pain symptoms of low back, hip and knee correlated significantly with the lateral asymmetry caused by incorrect length of the prosthesis. Independently of the side of amputation, the unilateral sciatica and chronic hip pain occurred mainly on the long leg side. Physical activity of the lower limb amputees seemed to correlate with the suitability of the length of the prosthesis, and was unrelated to the length of the amputation stump.

Introduction

Being a weight bearing substitute for a lost part of the lower extremity, the prosthetic limb should be of correct length to fulfil its biomechanical task. To avoid lateral imbalance in standing, walking, and running, the length of both exo and endoprosthesis ought to be adjusted to the length of the contralateral lower extremity.

In spite of the technical development in prosthetics, assessment of the length of the prosthesis still takes place with conventional clinical methods e.g. by direct tape measurement or indirectly by estimating the heights of the iliac crests or other bony prominences in the upright position. Devices have been developed e.g. by Hirschberg and Robertson (1972) for determining the level of pelvis.

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Clinical methods for measuring leg length inequality, however, contrary to general belief, have proved to be inaccurate and even misleading with observer error of ±10 mm or even more (Nichols and Bailey, 1955; Clarke, 1972; Morscher, 1977) as compared with the results of significantly more accurate radiographic measurements. The errors in clinical measurements are partly due to difficulties in locating the exact bony points for measurement through layers of soft tissues, and partly because of the prevalence of iliac asymmetries (Ingelmark and Lindström, 1963). The amputee's subjective opinion about the correct length of the prosthetic limb may also be misleading, particularly if the previous prosthesis has been of incorrect length. A rather common belief has been that walking with a short prosthesis should be easier than with one of equal length to the contralateral lower extremity.

On the other hand, a pelvic tilt caused by leg length inequality of even less than 10 mm is nearly invariably compensated with a functional scoliosis and associated with a varus position of the hip joint on the long leg side (Krakovits, 1967; Gofton and Trueman, 1971; Clarke, 1972). These mechanisms evidently have a predisposing role in the aetiology of chronic low back and hip pain symptoms and in the development of degenerative hip disease (Gofton and Trueman, 1971; Clarke, 1972; Heufelder, 1979; Friberg, 1983). The criteria for the optimal length of lower limb prostheses generally differ for below-knee and above-knee prostheses. A shortening up to 2 cm (Krämer et al, 1979) of above-knee prosthesis is generally allowed for ground clearance in the swing phase of walking. However, a shortening of not more than 1 cm, and for suction socket prostheses with minimal piston action only 6 mm or even less, has been suggested by Duthie and Bentley (1983). Recommendations to make a below-knee prosthesis full length and to avoid prostheses longer than the contralateral lower extremity are probably in accordance with the current general opinion.

The aim of this study was to find out how the above mentioned criteria for the length of lower limb prostheses are in fact satisfied, and to study the correlation of correct and incorrect prosthesis length with the incidence and severity of chronic low back, hip and knee pain symptoms in lower limb amputees.

Material and methods

This study comprises a series of 113 Finnish war-disabled lower limb amputees of whom 84 subjects had a below-knee prosthesis and 29 an above-knee prosthesis. The amputation was unilateral in all cases but one who had undergone an above-knee amputation and a contralateral below-knee amputation. In four cases a total hip replacement had been performed, the endoprosthesis being on the amputated side in one case and on the non-amputated side in three cases. The primary amputations were made during the wars 1939–40 and 1941–44, 39 to 45 years before this study.

To record the complaints associated with the amputation and the prosthesis, the patients were interviewed with a questionnaire and by personal inquiry. Special attention was drawn to symptoms of low back, hip and knee joints and to their laterality.

The clinical and radiological examinations were performed in 1983–84 at the Central Military Hospital, Helsinki, at the Tampere Radiological Center, Tampere, and at the Military Hospital 3, Kouvola. The majority of the amputees came to examination from the Kaskisaari Rehabilitation Center of the Fraternity Association of War Invalids.

Radiological assessment of the length of prostheses

The length discrepancy between the lower limb prosthesis and the contralateral lower extremity was measured with a weight-bearing radiographic method developed by the author (Friberg, 1983). In this method, the patient stands in front of a chest X-ray stand with straight knees and the weight equally distributed between both legs. A 15 cm broad block between the heels keeps the loading axes of the legs parallel and the positioning of the patient reproducible. A gonad shield supplied with an O-shaped plastic tube partly filled with mercury is strapped to the patient (Figs. 1 and 2). To avoid swaying the patient is advised to lean

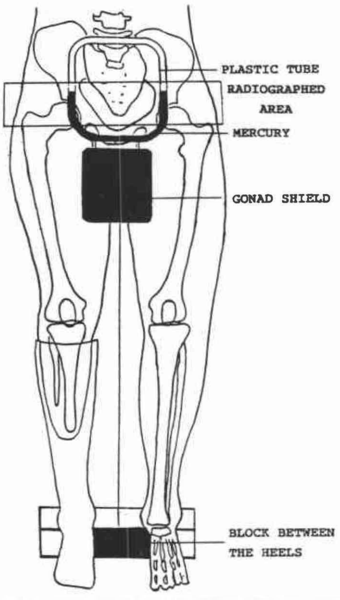

Fig. 1. Equipment and positioning of the amputee for measurement of the length of the prosthetic limb as compared with the length of the contralateral lower extremity (=the heights of the femoral heads).

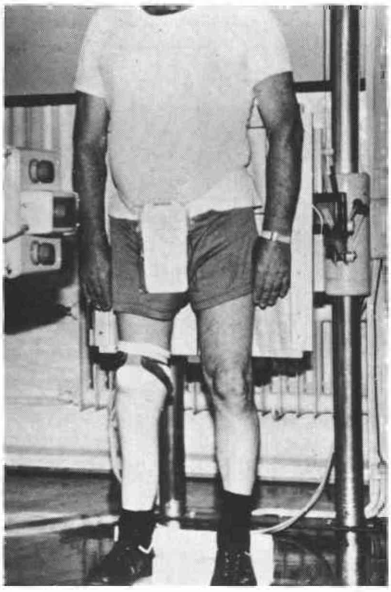

Fig. 2. Weight bearing radiographic measurement of the discrepancy between the length of lower limb prosthesis and contralateral lower extremity.

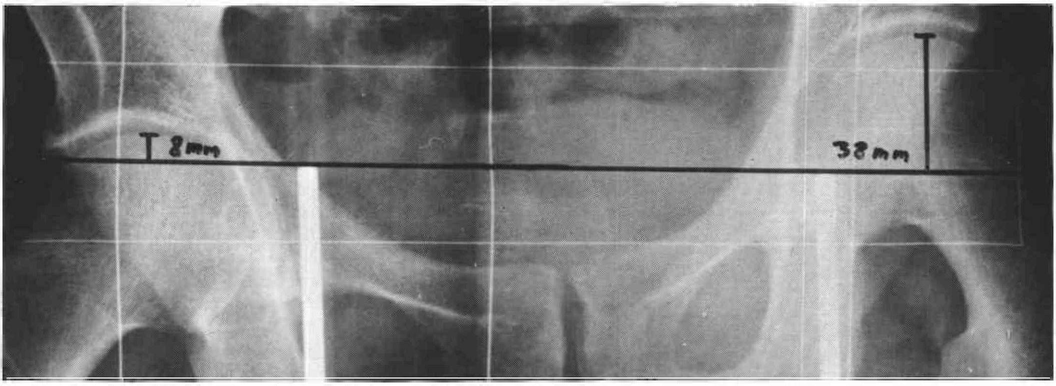

Fig. 3. A radiograph taken for measurement of the length of lower limb prosthesis. In this case there is 30 mm shortening of the prosthetic limb (right).

gently against the cassette holder with both buttocks. The central X-ray beam is focused on the pubic symphysis, and an A-P radiograph of both hip joints is taken. A horizontal reference line is drawn on the radiograph through the tops of the roentgen positive mercury pillars, from which the distances of the highest articular points of both femoral heads are measured (Fig. 3). The difference of the heights of femoral heads indicates the inequality of the weight-bearing lower extremities.

As the distance of the X-ray tube is constant and long enough, the magnification error is insignificant and can be ignored. The main source of error, unequal extension of the knees, is easily avoided by proper positioning of the patient.

Clinical examination

Special attention was paid to the pelvic tilt, lumbar scoliosis and other static body asymmetries in erect posture, which, if necessary, were radiologically documented. A block of equal thickness to the leg length inequality measured, was then placed under the foot of the shorter limb to reveal the subjective, clinical and radiological response of the body to the equalization of the pelvis. If the response was positive, i.e. the patient experienced the lift as comfortable and balancing, and the scoliotic curve straightened, the patients were advised to try a fixed lift under the shoe of the short leg before making a decision to have a permanent change in the length of the prosthesis.

Results

The mean age of the patients was 65.1 years (range 54 to 80 years), the mean length 173.5 cm (range 158 to 189 cm) and the mean body mass 80.9 kg (range 51 to 102 kg). The mean length of the above-knee stumps was 19.8 cm (range 8 to 30 cm) and of below-knee stumps 22.4 cm (range 12 to 28 cm).

Length of the prostheses

Though a majority (78.8%) of the amputees were of the belief that their prostheses were of equal length with the contralateral lower extremity, the length discrepancies were extremely prevalent and significant, ranging from a shortening of 47 mm to a lengthening of 40 mm (Table 1). Of the total group, the length discrepancy was more than 10 mm in 66.4% and more than 20 mm in 33.6% of the cases (Table 2). For comparison, in a group of 359 symptom-free Finnish Army conscripts aged 17 to 24 years (Friberg, 1983), leg length inequality of less than 10 mm occurred in 84.5% of the cases, and more than 20 mm in one case only.

In below-knee prostheses, the length was appropriate (length discrepancy less than 5 mm) in only 10 (11.9%) out of 84 patients, and in

Table 1. Subjective opinion of amputees about the length of the prosthesis and the ranges of measured length discrepancies.
("+" signs lengthening and "−" shortening of prosthetic limb)

Prosthesis felt	N	%	Ranges of measured length discrepancy
Equal	89	78.8	−47 mm to+37 mm
Shorter	17	15.0	−37 mm to+15 mm
Longer	7	6.2	−23 mm to+40 mm
Total	113	100.0	−47 mm to+40 mm

Table 2. Leg length inequality (difference of the height of femoral heads) in bipedal standing of 113 amputees with lower limb prostheses.

Leg length inequality mm	N	%
0–9	38	33.6
10–19	37	32.7
20–29	23	20.4
30 or more	15	13.3
‹10 mm	38	33.6
›10 mm	75	66.4
›20 mm	38	33.6
›30 mm	15	13.3

above-knee prostheses (discrepancy less than 10 mm) in only 7 (24%) out of 29 cases. In 17 cases (15%) out of the total the prosthesis was on average 14.4 mm longer than the contralateral lower extremity (Table 3).

Accuracy of radiological measurements

In a previous study with non-amputees, the mean error between two or more subsequent measurements was 0.6 mm (range 0 to 2 mm) Friberg, 1983). In the present study, a re-examination was made in 10 cases and in a further 10 cases after correction of the incorrect length of the prosthesis or by insertion of a lift equivalent to the leg length inequality under the foot of the short leg. the mean error between these measurements was 1.2 mm (range 0 to 4 mm).

Low back pain

Chronic low back pain symptoms were prevalent in the present series of lower limb amputees. Only 6 patients (5.3% of the total series) were completely free from low back pain. In altogether 25 patients, however, the low back symptoms were occasional and fairly mild. In these patients the mean leg length discrepancy was 6.1 mm. The mean discrepancy in 32 amputees with frequent or constant and severe low back pain was 21.7 mm. The difference between the mean leg length discrepancies in these two groups was statistically highly significant ($p < 0.001$, $t=4.65$). A chronic unilateral sciatica was present in 23 cases, the radicular pain radiating into the longer lower extremity in 14 (60.8%); of the cases, independently of the side of the amputation, the mean discrepancy of leg length was 19.9 mm. Sciatica occurred on the short leg side in 9 cases, the mean leg length inequality being 12.6 mm.

Hip pain

Of the total material, 30 amputees were without any significant hip pain symptoms. In these patients, the mean length discrepancy of lower extremities was 8.8 mm. In 36 patients the hip pain symptoms were bilateral and the mean leg length discrepancy 14.8 mm. In 47 cases, the chronic hip pain symptoms were unilateral, the mean leg length discrepancy being 16.3 mm. The unilateral hip pain symptoms occurred on the side of the longer lower extremity in 61.7% of the cases, independently of the side of amputation (Table 4).

Knee pain

Significant knee joint pain was absent in 21 of the amputees. The mean leg length inequality in these patients was 7.6 mm. Only two above-knee amputated subjects were free from knee pain.

Bilateral knee pain symptoms in below-knee subjects occurred in 33.3% of the cases, the mean leg length inequality being 15.6 mm. In patients with unilateral knee symptoms the leg

Table 3. Suitability of the length in lower limb prostheses

Prosthesis	Total N	Fit N	Too short N	Too short × mm	Too long N	Too long × mm
Below-knee	84	10	60	15.9	14	15.4
Above-knee	29	7	19	28.9	3	10
Total	113	17	79	19.0	17	14.4
Per cent	100	15	70		15	

Table 4. The location of unilateral hip pain symptoms and leg length inequalities (mean errors of the prosthesis length).

Pain symptoms in the hip of	Total N	Total %	Longer limb N	Longer limb $\bar{x}$	Shorter limb N	Shorter limb $\bar{x}$
Amputated limb	15	31.9	4	10.0 mm	11	18.9 mm
Non-amputated limb	32	68.1	25	18.1 mm	7	16.4 mm
Total	47	100	29	61.7%	18	38.3%

length inequality was 12.8 mm. The complaint occurred on the amputated side in 25% of the cases and on the non-amputated side in 75% of the cases.

Sporting activity of the amputees

Physical activities like jogging, skiing or gymnastics were carried out daily by 43 below-knee amputees. The mean leg length inequality in these amputees was 9.7 mm. In 25 below-knee subjects without daily physical activity, the mean leg length inequality was 18.5 mm. The difference between these means proved to be statistically significant ($p<0.01$, $t=2.95$). The mean length of the stumps in these two groups showed no difference, being 18.9 cm and 18.5 cm. Similarly, in 12 physically active above-knee amputees, the leg length discrepancy was 17.3 mm, and in 12 inactive above-knee amputees it was 22.6 mm, the difference, however, being statistically not significant ($p<0.1$). No difference between the mean lengths of the stumps was found.

Discussion

Contrary to subjective beliefs, most lower limb amputees in the present series were found to use a prosthesis of incorrect length. Also in non-amputated material, subjects with a leg length inequality of up to 20 mm were mostly unaware of the asymmetry (Friberg, 1983). In spite of the advanced age of the amputees, experimental equalization of the pelivc tilt with a shoe lift was generally experienced as comfortable and balancing. On examination, a significant straightening of the lumbar scoliosis could mostly be observed and documented radiologically. In an ongoing study, the long-term effects of correcting the length of the prosthesis are being followed-up. Until now, correction of the length of the prosthesis has mostly been favourable with an alleviation of low back and hip pain symptoms and a significant improvement in walking pattern, particularly after shortening of a prosthesis which was too long.

The assessment of the severity of low back, hip, and knee pain symptoms is difficult, but the present results clearly suggest that the amputees with symmetrical length of the prosthesis have significantly less pain symptoms than those with marked lateral asymmetry. Accordingly, the amputees using a prosthesis of acceptable length seemed to be physically more active than those with a prosthesis of incorrect length.

Likewise in non-amputees, the unilateral symptoms such as sciatica or hip pain (Gofton and Trueman, 1971; Clarke, 1972; Friberg, 1983) occurred in lower limb amputees mostly on the long leg side, regardless of the side of the amputation. This suggests that, not only the amputation but the incorrect length of the prosthesis is a significant factor in causing discomfort, torsion and unequal distribution of load in the knee and hip joints and in the lumbar spine.

Pelvic tilt caused by unequal length of the lower extremities results in a compensatory functional scoliosis which is mostly concave to the long leg side (Ingelmark and Lindström, 1963; Heufelder, 1979), and in a varus position of the hip joint on the same side (Gofton and Trueman, 1971; Clarke, 1972; Friberg, 1983). (Figs. 4, 5). Lateral bending of lumbar motion segments compress the disc on the concave side, causing a protrusion toward the concavity. In connection with lumbar lordosis, this makes the posterolateral part of the disc bulge toward the spinal nerve root on the long leg side which may be a cause for radicular symptoms (Friberg, 1983).

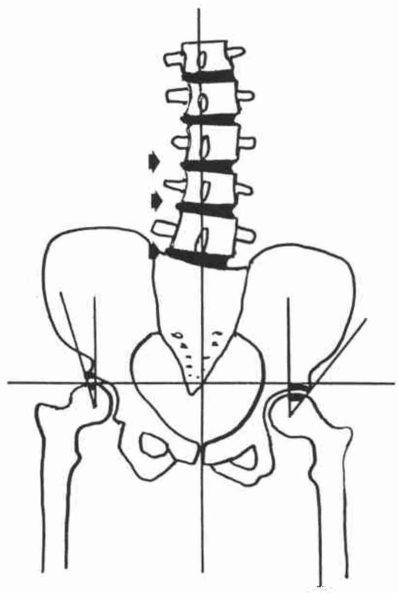

Fig. 4. The biomechanical effects of a leg length inequality—pelvic tilt to the short leg side—varus position of the long leg hip (note Wiberg's angle)—functional scoliosis toward the short leg—protrusion of discs to the concavity.

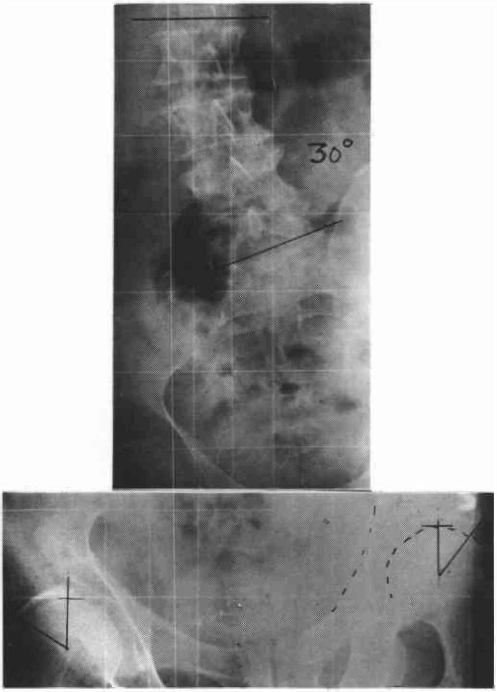

Fig. 5. A case, with an above-knee prosthesis on the right side which was 40 mm too short, suffering from constant low back and left hip pain since amputation in 1944. Note: diminution of weight-bearing articular surface of the longer lower limb as illustrated by Wiberg's angle, and the functional scoliosis with wedge-shaped intervertebral spaces and axial rotation of the vertebrae (radiographs taken in a standing posture). The response to the correction of the prosthesis length was excellent.

The varus position of the long leg hip as illustrated by Wiberg's angle (Krakovits, 1967; Morscher, 1977) results in a diminution of weight-bearing articular area of the joint, thus speeding the degenerating breakdown in the hip. Concurrent occurrence of symptoms from lumbar spine and hip, the hip-spine syndrome (Offierski and Macnab, 1983), was common among lower limb amputees, evidently because of the high prevalence of lateral asymmetries due to incorrect length of the prostheses.

In the light of present results, conventional assessment of the length of lower limb prostheses with clinical methods seems to be inaccurate and unreliable. The range of errors in the length of the lower limb prostheses was as high as 87 mm (47 mm too short to 40 mm too long). The weight-bearing radiographic method for measurement of leg length inequality offers an accurate, reliable and simple tool to adjust the correct length for lower limb prostheses. The costs of radiography are minimal when compared with the expense of manufacturing a prosthetic limb. Paricularly in adjusting the first prosthesis for a recently amputated patient, the assessment of the correct length of the prosthesis appears imperative to allow the subject to adapt from the beginning to symmetry of the lower extremities, to train him to walk without a limp, and to avoid malpositions and development of degenerative changes in hip, knee and lumbar spine.

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