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A Roentgenological Study of the Stump–Socket Contact and Skeletal Displacement in the PTB-Suction Prosthesis

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ABSTRACT

The PTB-suction prosthesis has been studied by a roentgenological technique. There is complete contact between the skin of the stump and the plastic inner surface of the socket. The movement of the stump in the socket is minimal. The displacement of the skeletal stump is reduced to half in the PTB-suction prosthesis, compared with the strap-suspended PTB prosthesis. As a result, the stability between stump and socket is increased, provided that the stump is sufficiently long. Skin sores are avoided. The prosthesis, when adequately fitted, guarantees a good circulation within the stump and a cosmetically favourable fit with a feeling of walking with "a normal leg".

INTRODUCTION

The construction of the PTB prosthesis (PTB= Patella Tendon Bearing) was a result of many years of study of the biomechanics of walking after below-knee (BK) amputation (1). This excellent prosthesis fits the needs of about 90% of BK amputees (2, 3). In some patients the PTB prosthesis still gives rise to problems (sensation of instability and development of contact sores). This was a challenge to try to develop a satisfactory alternative for the BK amputee. A prosthesis team consisting of members from the Een & Holmgren Orthopaedic Co. and the Department of Orthopaedic Surgery started the first clinical trials 1969 with an analogue to the above-knee suction prosthesis (4), called a PTB-suction prosthesis. The preliminary results were reported by Grevsten & Marsh in 1971 (5).

Roentgenological examinations have previously been found of value in studies of the relationship between prosthesis and stump (6, 7). The fit and function of the PTB-suction prosthesis have therefore been studied by similar methods. The present roentgenological investigation of the stump–prosthesis relationship in BK amputees was undertaken with the aim of studying (i) the contact between stump and socket, and (ii) the relation of the skeletal stump to the soft tissue in different stride moments.

MATERIAL AND METHODS

Patients

The study was made on 22 patients of ages 28 to 66 years with below-knee amputations (unilateral in 8 women and 13 men, and bilateral in 1 man). The length of time between the amputation and the investigation varied from about one month to 42 years.

Technical comments on the prostheses

The check-up of the fit of the prostheses was carried out in collaboration with only one prosthetist (L. Marsh). The PTB-suction prosthesis was initially constructed with the socket and the rest of the prosthesis as one unit. Later the socket was made as a detachable component, which was found to have considerable advantages for the patient. The attached socket was made of an epoxy resin (Araldite®). The detachable socket has been made more elastic and consists of 60% Araldite and 40% softener 617 W 1 (Wersamide®). A valve (Total Contact Valve, TVC-100 (Reddot®), A. J. Hosmer Corp., Campbell, California, USA) is fitted into the bottom of the socket. The foot construction of the prosthesis is the same as in the current PTB prosthesis (1).

Roentgenological technique (Fig. 1)

A horizontal beam was used, with its central direction at right angles to the film. The film–focus distance was always 100 cm and the film cassette was placed in direct contact with the prosthesis–stump unit. The frontal projection was not used because of the greater uncertainty of the reproducibility and film geometry with this projection.

Stride positions in roentgenological examination of prosthesis–stump unit (Fig. 1)

The roentgenological examination was carried out under four different conditions of weight-bearing (simulated stride positions) (6):

Stride position A: The prosthesis bearing no weight and lifted slightly from the ground.

Stride position B: The body weight distributed equally over both legs, with the prosthesis in the heel-strike position. Equally distributed body weight means that the patient assumed a position ready for walking, rocked for-

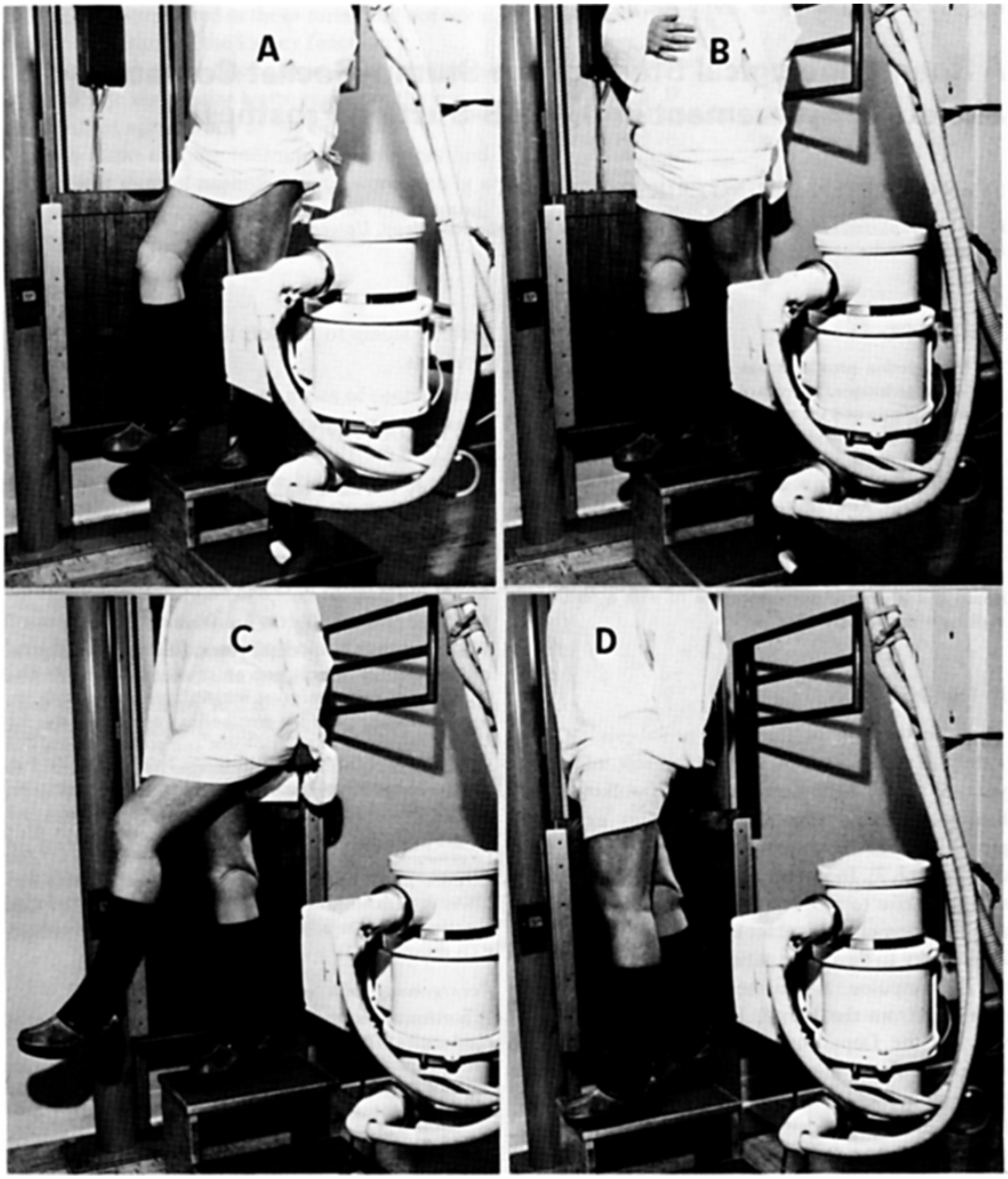

Fig. 1. Stride position A, B, C and D at the roentgenological examination of the prosthesis–stump unit.

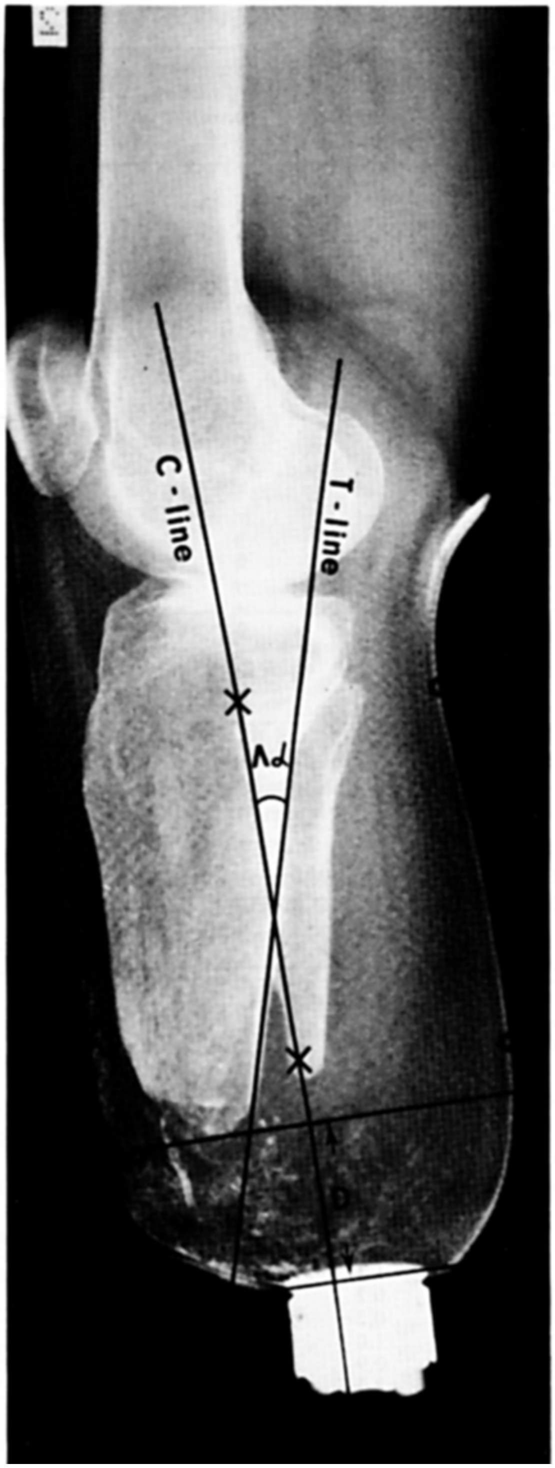

Fig. 2. The reference lines for evaluation of the roentgenograms. Line C is the central line through the socket of the prosthesis. Line T is the reference line for the skeletal stump and consists of the posterior ridge of the tibia and its extension. Λα designates the angle between lines C and T. D is the distance between the tangent drawn from the end of the skeletal stump and the tangent from the bottom of the socket. These two tangents are drawn at right angles to line C.

wards backwards and then remained in the position in which he considered the load to be equally distributed. This was thus the patient's subjective idea of equal body weight distribution.

Stride position C: The full body weight is transferred to the prosthesis stump unit, with the contralateral foot lifted from the ground.

Stride position D: The body weight is distributed equally between the legs and with the prosthetic side at the stage of the walking cycle immediately prior to toe lift. (For equal body weight distribution, see B).

In order to increase the reproducibility of the measurements as far as possible in evaluating the movements of the skeletal stump on changing from one stride position to another, some geometric constructions were introduced into the roentgenograms (Fig. 2). One of these was a central line, line C, through the socket. The posterior ridge of the tibia with its extension was chosen as reference line for the skeletal stump (line T; see Fig. 1, and Discussion on Method). The tangent to the end of the stump bone and the tangent to the bottom of the socket were drawn at right angles to line C. The distance between these lines constituted a measure of the position of the bone.

Determination of position of skeletal stump based on construction lines (Fig. 2)

I. The displacement of the body stump inside the socket in the various stride positions was obtained by measuring the distance between the two tangents for position A and subtracting the corresponding values for positions B, C and D, respectively.

II. The sagittal displacement of the body stump was determined by measuring the angle between lines C and T in position A and subtracting the corresponding angles obtained in positions B, C and D, respectively.

The main parameters for evaluating the relationship between stump and socket were:

(1) differences in vertical displacement between position A and the other position B–D, and

(2) angular differences between the direction of the tibia in position A and positions B–D in the sagittal plane.

Clinical data (Table I)

The patients with the PTB-suction prosthesis were followed up at 1 month, 3 months, 6 months, 1 year and then annually after the first fitting of the prosthesis. The longest observation time was 4 years. Information was obtained on the extent to which the prosthesis had been used, the feeling of security with the prosthesis, the skin condition and any problems with skin sores. The extent to which the PTB-suction prosthesis was used was graded as follows:

1. PTB-suction prosthesis used as the primary prosthesis (+)
2. PTB-suction prosthesis used as an alternative (once or a few times weekly) (0)
3. Another prosthesis used entirely (−)

Table I. *Clinical observations*

Name	Age	Sex	Amount of soft tissue 0, +, ++	Stump length (cm)	Airspace in the socket on X-ray	Suitability of suction prosthesis −, 0, +
J. J.	34	♀	++	5	−	−
J. H.	49		+	19.5	−	0
H. H.	66		++	15	−	0
G. T.	30	♀	+	12	−	−
H. L.	36		+	18.5	−	0
I. W.	37	♀	++	17.5	−	0
J. S.	55		++	14.5	−	0
J.-E. P.	52		++	18	−	+
N. L.	33	♀	++	22.5	−	+
R. K.	40	♀	++	14	−	+
J. T.	28		++	18.5	−	+
L. L.	48		+	15	−	0
K.-O. E.	43 dx		++	17	−	+
K.-O. E.	43 sin		++	18	−	+
S. A.	48		++	19.5	−	−
S. D.	36		++	12.5	−	+
G. K.	57		+	17	−	0
L. O.	34	♀	++	15.5	−	+
K. M.	34		+	18	−	+
R. H.	47	♀	++	14.5	−	0
N. W.	38		++	10	−	−
H. G.	53	♀	++	13.5	−	+
E. F.	46		+	18	−	0

Table II. *Skeleton displacement (down in the socket) in various stride positions*

Name	Age	Sex	A D_A	B $d_B=D_A-D_B$	C $d_C=D_A-D_C$	D $d_C=D_A-D_D$
J. J.	34	♀	7.4	1.1	1.2	1.2
J. H.	49		4.7	0.9	0.7	0.8
H. H.	66		4.4	0.3	0.4	0.6
G. T.	30	♀	4.4	1.2	0.9	0.9
H. L.	36		3.7	0.5	0.9	0.5
I. W.	37	♀	2.5	1.0	1.2	0.9
J. S.	55		4.6	1.0	1.2	0.9
J.-E. P.	52		2.1	0.4	0.4	0.5
N. L.	33	♀	5.7	2.1	2.8	2.5
R. K.	40	♀	5.0	0.6	0.6	0.7
J. T.	28		3.4	1.2	1.1	1.0
L. L.	48		2.0	0.4	0.4	0.3
K.-O. E.	43 dx		4.6	1.0	1.4	1.0
K.-O. E.	43 sin		3.9	0.5	0.2	0.4
S. A.	48		4.5	0.5	0.2	0.6
S. D.	36		8.2	1.0	1.0	0.9
G. K.	57		2.6	0.8	0.9	0.8
L. O.	34	♀	4.2	2.3	2.3	2.0
K. M.	34		3.3	0.9	0.9	1.0
R. H.	47	♀	4.5	1.9	1.9	1.7
N. W.	36		4.8	1.5	1.8	1.8
H. G.	53	♀	4.2	2.4	2.8	2.4
E. F.	46		3.5	0.7	0.9	0.6
			$M_{DA}=4.26$ S.D.=1.47 $n=23$	$M_{dB}=1.05$ S.D.=0.61 $n=23$	$M_{dC}=1.13$ S.D.=0.74 $n=23$	$M_{dD}=1.04$ S.D.=0.62 $n=23$

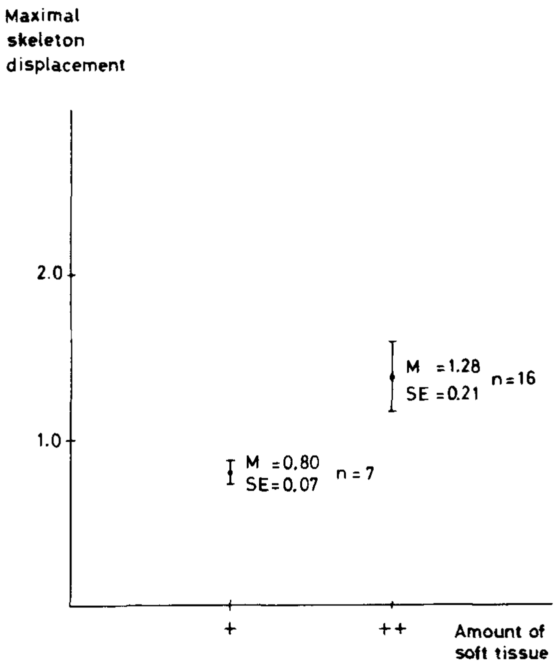

Fig. 3. Maximal skeletal displacement is defined as the difference D_A–D_C (Table II). For the definition of amount of soft tissue, see text under Clinical data. The mean skeletal displacement of soft tissue of grade + differs significantly from that of soft tissue of grade ++.

Clinically, the stump length was measured from the medial joint space to the end of the stump bone. The soft tissues were carefully pulled down and the distance between the end of the tibia and the soft tissue end of the stump was measured with a tape measure, which gave a rough idea of the amount of soft tissue. The amount of soft tissue distal to the end of the bone was graded: 0, + and ++, where 0=<1 cm, +=1–2 cm and ++=>2 cm. The lengths of stumps varied between 5 and 22.5 cm, and only four measured 12.5 cm or less. These were considered unusable for the PTB-suction prosthesis.

RESULTS

Total contact, the absence of a gap between the amputation stump and the socket of the prosthesis, was found in all 23 prostheses in all four different positions.

Downward displacement of skeletal stump (Table II)

The downward movement of the bony stump in the socket on changing from one position to another was maximum for position C, with a mean value (Md_C)=1.13 cm. The mean skeletal displacements for positions B and D were only slightly lower, the difference not being statistically significant. The ranges of displacement for the 4 positions were:

Table III. *Skeleton displacement (tibia angulation) in various stride positions*

Name	Age	Sex	A $\Lambda\alpha_A$	B $d\Lambda\alpha_B=\Lambda\alpha_A-\Lambda\alpha_B$	C $d\Lambda\alpha_C=\Lambda\alpha_A-\Lambda\alpha_C$	D $d\Lambda\alpha_D=\Lambda\alpha_A-\Lambda\alpha_D$
J. J.	34	♀	20°	−5°	−2°	−5°
J. H.	49		5°	+3°	+2°	+3°
H. H.	66		15°	−1°	0°	
G. T.	30	♀	11°	−1°	+1°	−3°
H. L.	36		11°	−1°	+1°	−3°
I. W.	37	♀	8°	+1°	0°	+2°
J. S.	55		16°	+1°	0°	+2°
J.-E. P.	52		6°	+1°	+2°	−1°
N. L.	33	♀	5°	+6°	+1°	+3°
R. K.	40	♀	11°	+5°	+5°	+6°
J. T.	28		2°	+3°	0°	+3°
L. L	48		8°	+1°	+2°	0°
K.-O. E.	43 dx		5°	+2°	−3°	+2°
K.-O. E.	43 sin		1°	+4°	+3°	+4°
S. A.	48		10°	0°	+4°	+1°
S. D.	36		10°	+5°	+5°	+5°
G. K.	57		8°	0°	−1°	0°
L. O.	34	♀	7°	+2°	+1°	−2°
K. M.	34		8°	+2°	+2°	+2°
R. H.	47	♀	12°	−1°	0°	−1°
N. W.	36		18°	+2°	+1°	−8°
H. G.	53	♀	15°	+11°	+10°	+10°
E. F.	46		7°	−1°	−3°	−5°
			$M\Lambda\alpha_A$=9.5°	$M_d\Lambda\alpha_B$=+1.7°	$M_d\Lambda\alpha_C$=+1.4°	$M_d\Lambda\alpha_D$=+0.7°
			S.E.=1.0°	S.E.=0.7°	S.E.=0.6°	S.E.=0.8°
			n=23	n=23	n=23	n=23

2.0–7.4 cm for position A and additionally 0.3–2.4, 0.2–2.8 and 0.3–2.5 for positions B, C and D respectively. Fig. 3 illustrates the direct relationship between skeletal displacement and amount of soft tissue.

Skeletal displacement in the sagittal plane – tibial angulation (Table III)

The measurement of the angle between line C and line T (Fig. 2) was 9.5 degrees (average) in position A. The change in tibial angulation in the various conditions of weight-bearing meant that the soft tissues were pressed together in the direction in which the displacement took place. It was calculated that in all stride positions except D the mean angular displacement of line T anteriorly was significant, with a mean value of 1.7° in position B, 1.4° in position C and 0.7° in position D. This meant that anteriorly the soft tissues were compressed mainly in positions B and C, i.e. on heel-strike of the prosthesis.

DISCUSSION ON METHOD

For an objective evaluation of the functional fit of a prosthesis, roentgenological examination is a suitable method. Its usefulness in this connection has been demonstrated in studies by Erikson & Lemperg (6) and Erikson & James (7).

In the former study the action of the skeletal and soft tissue parts of the stump (pistoning action) in the PTB prosthesis was analysed. The roentgenological examinations were performed under conditions simulating stride positions. The same model was used in the present investigation. It consists of four representative static chief phases of the walking cycle. Stride position A represents the suspended prosthesis in the swing phase, B the heel-strike position at the start of the stance phase (same load on both legs), C full weight-bearing on the prosthesis during the swing phase of the other leg, and D the toe contact position at the end of the stance phase (same load on both legs). The aim is to give an approximate reproduction of the stump movements in the socket during the walking cycle. Obviously the kinetic loads in normal walking are quite different from the loads in these static simulations, but this investigation only concerns tissue displacements.

To allow of the best possible reproducibility in the measurements on the roentgenograms, some geometrical constructions were introduced into each film. A central line (line C) and a line along the dorsal ridge of the tibia (line T) were drawn. Line T describes the relative direction of the tibia, as the dorsal ridge is in itself anteverted about 10°. Furthermore, the alignment of the prosthesis has a basic flexion angle of 5° (and 5° abduction) (1).

To measure the downward displacement of the tibia in the socket, measurements were made along line C. In spite of strict precautions at the X-ray examinations there is some inaccuracy in these measurements. Among them the magnitude of the reduction factor due to magnification is about 0.85. This may vary a little owing to minor changes in distances between the extremity and the film.

When measuring the antero-posterior motion of the tibia the use of angular differences increases the accuracy. Angles are of course quite unaffected by changes in magnitude. Erikson & Lemperg measured the downward displacement of the skeletal stump inside the prosthetic socket as the distance between the tibial ridge and socket, which differs a little from the present measurement technique. This minor methodological difference does not prevent a comparison between the results, however. In all other respects the X-ray technique was the same.

GENERAL DISCUSSION

The pistoning action on walking with a PTB prosthesis involves a downward displacement of the stump in the socket during the stance phase. During the swing phase the socket moves downwards due to force of gravity and a centrifugal effect. The stump movement can be divided into two components. One of them is the displacement of the soft tissue, the other is the skeletal movement. When the soft tissues of the stump are moving freely in relation to the socket they are affected by the natural gait motion of the leg, and the downward displacement in the socket takes place on weight-bearing. The gait motion consists of a pendular and a rotational movement (4, 8, 9, 10). In the rotational movement the leg gradually rotates inwards during the stance phase and rerotates in the other direction in the swing phase. This complex mechanism means that when weight bearing occurs the skin and soft tissues are forced in a proximal direction according to a regular pattern, partly by compression and partly by traction combined with rotation. Because of a lack of absolute fixation and mechanical inertia, the prosthesis does not follow this movement. The inwardly directed

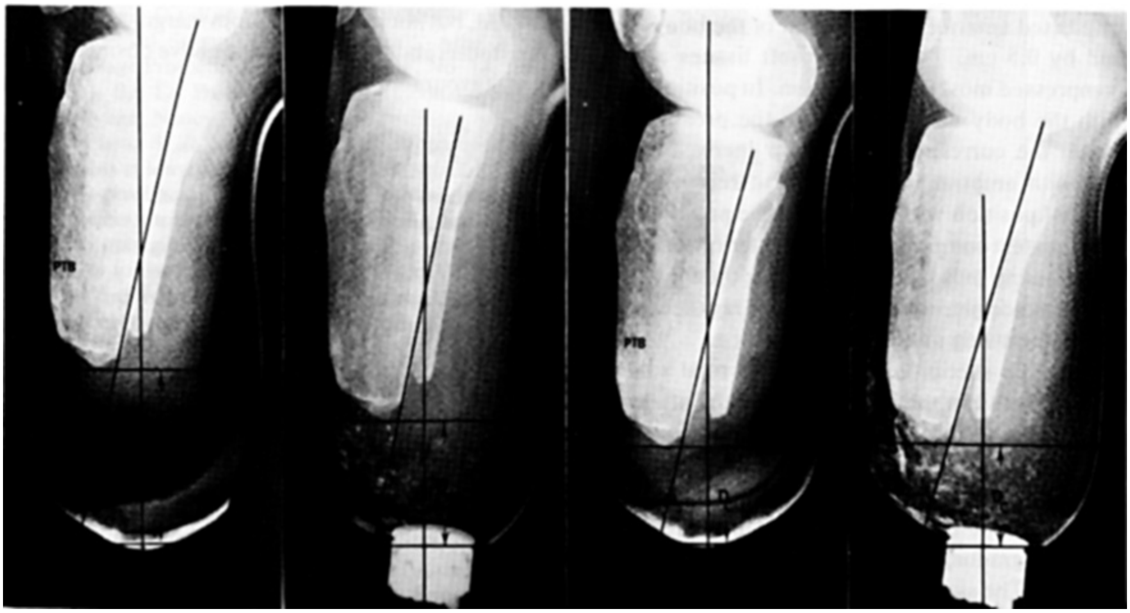

Fig. 4. An illustration of the difference in downward displacement of the skeletal stump between the PTB and PTB-suction prostheses. Both prostheses are shown in stride position A and C. D_A and D_C denote the distance between the skeletal end and the bottom of the socket in stride position A and C. The interposition of air is easily seen in position A of the PTB prosthesis.

torsional movement—the so-called screwing home mechanism of the leg—combined with the movement of the stump in the central part of the soft tissues even accentuates the displacement pattern, with the effect that sores easily appear on critical skin areas.

This present roentgenological study of the PTB suction prosthesis for BK amputees has elucidated the positions of the skeletal stump in the prosthesis during the various phases of the walking cycle.

COMMENT

The downward displacement of the skeletal stump in the socket becomes maximal during the swing phase of the other leg (position C), with a mean value of 1.13 cm (Table II). This value differs significantly from the corresponding skeletal displacement with the PTB prosthesis (6) 2.25 cm (S.D. = 1.45, $n=24$)—a value previously unpublished but now calculated from the same case material. This difference can be explained entirely by the soft tissue displacement—the piston action—that takes place in the PTB prosthesis. The downward displacement of the skeletal stump in the socket with the PTB-suction prosthesis does not increase notably when the load increases from an even distribution between the two legs to weight-bearing on the prosthetic leg alone. The greatest skeletal displacement of only 1 cm thus occurs on changing from the stance phase to the swing phase and the reverse.

During the swing phase, air is interposed between the stump and socket in the PTB prosthesis (Fig. 4). During the stance phase all air does not disappear but remains in small pockets, where it may be sealed off. This is a mechanical event that may be of great importance (1) because the volume changes in sealed off air pockets are indicative of changes in pressure that are inversely related to the size of the air pockets. This may partly explain some problems that arise with the PTB prosthesis. Further, it stresses the importance of careful shaping of the socket so as to achieve total adhesive contact, (1, 12, 13, 14) without any compression around the stump end.

The angular displacement of the tibia in the sagittal plane has also to be considered. It constitutes a measure of the soft tissue compression anteriorly and dorsally in the sagittal plane. The greatest angular displacement of the tibia occurs in the position when the heel strikes the ground in readiness for the stance phase (position B), when the inclination of line T in relation to line C (Fig. 2 and Table III) increases in an anterior direction by a mean of 1.7°. With a 15 cm long stump this increase implies a calculated anterior displacement of the bony stump end by 0.5 cm. The anterior soft tissues are thus compressed most in this position. In position C, i.e. with the body weight borne on the prosthetic leg alone, the corresponding angular increase is 1.4°, still with anterior displacement in relation to the original position with no load on the prosthetic leg. The greatest compression of the anterior soft tissues of the stump thus takes place during the first instant of the stance phase of the prosthetic leg (heel strike) and in the swing phase of the other leg.

The PTB suction prosthesis gives total adhesive contact between the skin surface of the stump and the plastic surface inside the socket. Movements between the soft tissues and socket are reduced to a minimum at the skin surface. The displacements of the soft tissue mass take place mainly around the bone and gradually diminish in the direction towards the skin. The skeletal downwards movement is thus the chief action.

On weight-bearing, the pendular and rotational movements of the leg combine with the downward skeletal movement in the socket and movements take place between the skeleton and soft tissues. The stabilizing adhesive contact between the stump and socket give the muscle tissue an activating resistance during the walking movement (15). The whole movement pattern can be described as a muscle pump. That several patients have shown healing of skin lesions on the stump despite the fact that they have worn the PTB suction prosthesis during the healing periods indicates a favourable circulatory effect.

CONCLUSION

This study of the PTB-suction prosthesis for the below-knee amputee demonstrates a better contact between the stump and the socket in comparison with strap-suspended PTB prostheses. The calculated average difference in displacement between the two prostheses is 1.15 cm.

Reduced movements of soft tissue in the socket of the PTB-suction prosthesis diminish the movement of the entire prosthesis in relation to the amputated leg. On the other hand, the larger the amount of soft tissue, the greater the skeletal movements (Fig. 3), which relation may mean an improvement of the circulatory situation.

A reduction of the piston action gives the patient a feeling of walking with a "normal leg".

Last, but not least, the smooth margin between the prosthesis and the rest of the leg have cosmetically a very favourable effect.

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