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Multifunctional above-knee prosthesis for stairs' walking

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Abstract

The multifunctional above-knee prosthesis WLP-7R (Waseda Leg Prosthesis – type 7 Refined) described in this study allows amputees to descend and ascend stairs with no external power sources. With the hydraulic circuit mounted in the shank, the ankle joint and the knee joint mutually conterbalance during stance phase in stair walking as well as level walking so that the following performances are obtained. The yielding (flexing) of the knee joint is prevented and smooth advance from stance-phase to swing-phase is realized in level walking. The gradual yielding of the knee joint and the ankle joint while sustaining full body weight is realized in stair descent. Reciprocal stepping with sound and disabled legs during stair ascent is also realised although the powerful extension of the knee joint during stance phase is not possible. The performance of the WLP-7R was examined by a walking experiment in which amputees could descend and ascend the stairs as well as walk on a flat surface after approximately one hour's training.

Introduction

This paper deals with the multifunctional above-knee (AK) prosthesis having the function of permitting stair walking like normal subjects with no external power sources. There have been a few approaches to provide reciprocal walking on stairs (with both lower legs reciprocally advancing and landing on the next stair) by A/K prostheses (Mauch, 1968; Horn, 1972). The knee joints developed in these studies were mechanically locked during stance phase to provide gradual yielding of the knee joints. The fatal problem of these mechanisms lies in the fact that the control of hydraulic flow rate was so difficult that the amputees had to pay undue attention while walking on the stairs (Wagner & Catranis, 1954).

It can be approximately said that a mechanism actuating a knee joint must change its rigidity in three stages (Mauch, 1967). One is the free stage for swing phase, Two is the locking stage and the last stage has the intermediate rigidity of a knee joint for gradual yielding during stairs' descent. However, these stages could be changed continuously or smoothly not suddenly.

In this study a new hydraulic mechanism for above-knee prostheses was proposed and assembled in above-knee prosthesis WLP-7R (Waseda Leg Prosthesis-7 Refined). The proposed mechanism allows the gradual change of the three modes mentioned above. Especially it permits gradual yielding of the knee joint while sustaining full body weight so that the WLP-7R allows amputees to descend stairs in the same way as normal persons and to ascend with reciprocal stepping with no external power source for actuating the knee joint. The WLP-7R is the simplified and refined type of the WLP-7 (Koganezawa & Kato, 1987)

Multifunctional A/K prosthesis: WLP-7R

Figure 1 illustrates the basic structure and the mechanism of the WLP-7R. The most essential mechanism of the WLP-7R is that the cylinder of the knee joint hydraulically connects with that of the ankle joint, by which mutual counterbalance between the ankle joint and the knee joint is realized, which is basically similar to homolateral extensor reflexion. The port B is closed by the ankle piston as the ankle joint

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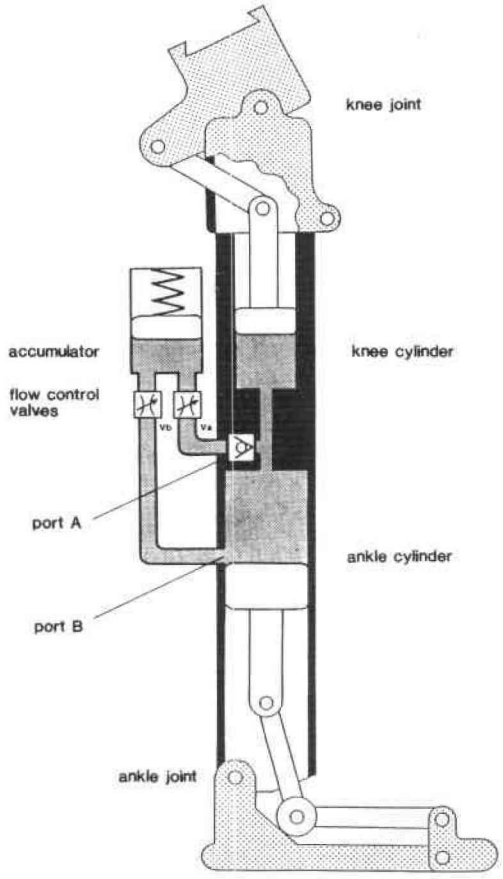


Fig. 1 Structure and mechanism of the WLP-7R.

dorsiflexes during a stance phase. Thereafter sudden yielding of the knee joint is prevented by hydraulic pressure which is produced by the dorsiflexion of the ankle joint. At the same time hydraulic energy is stored in the accumulator as spring force. This energy is released for the active extension of the knee joint during the next swing phase.

The appearance of the WLP-7R is shown in Figure 2. The structural material of the WLP-7R is CFRP (Carbon Fibre Reinforced Plastic; black part of the shank in Fig. 2) and duralumin. The weight of the WLP-7R below the knee joint is 2.4 kg which is approximately the same as a conventional A/K prosthesis.

The sequence of the mechanism during walking

(1) *Level walking*

Figure 3 shows the successive movements of the mechanical parts of the WLP-7R, which

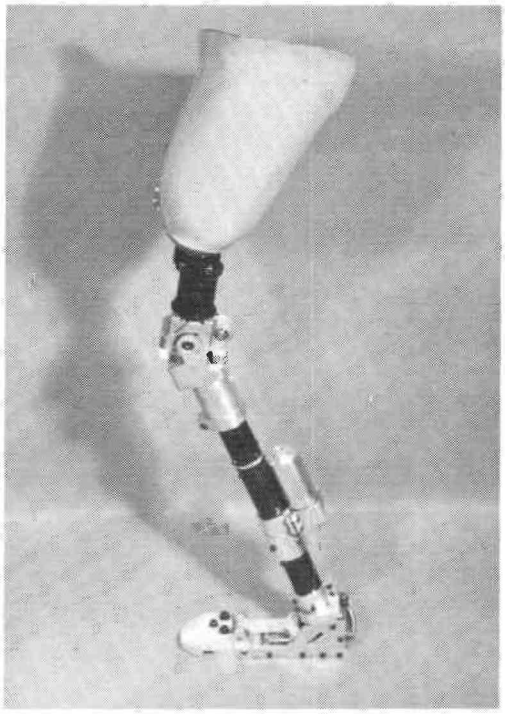
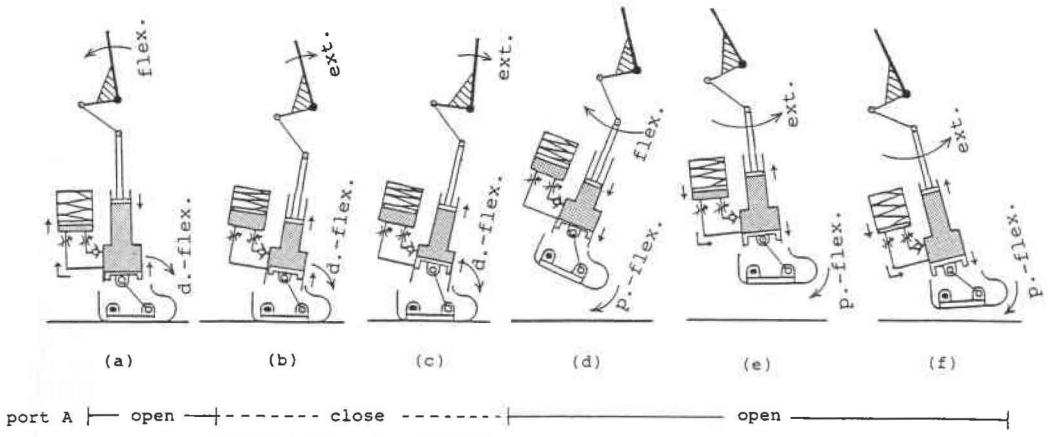


Fig. 2 The WLP-7R.

starts from the time of sole contact (Fig. 3 (a)). The port B is sequentially closed by the ankle piston as dorsiflexion is progressing and the ankle piston is pushed up during the stance phase. Hereafter dorsiflexion of the ankle joint hydraulically pushes the knee piston upward so that yielding of the knee joint is prevented (Fig. 3(b)). At the same time oil gradually flows into the accumulator via port A, of which the flow rate is adjusted manually by the needle valve. Flow rate of the port A determines the rigidity of the knee joint and the ankle joint. After dorsiflexion of the ankle joint is terminated at the end of the stance phase, the knee joint begins to flex gradually so that translation of phase from a stance to a swing is smoothly performed (Fig. 3(c)). The following sequence is consecutively performed after a swing phase starts. The knee joint begins to flex. → The knee piston is pushed down. → The ankle piston is pushed down (Fig. 3(d)). → The port B is opened. → The oil in the accumulator begins to flow back in the ankle and knee cylinders. → The knee joint is actively extended (Fig. 3(e)). → The next sole contact occurs (Fig. 3(f)).



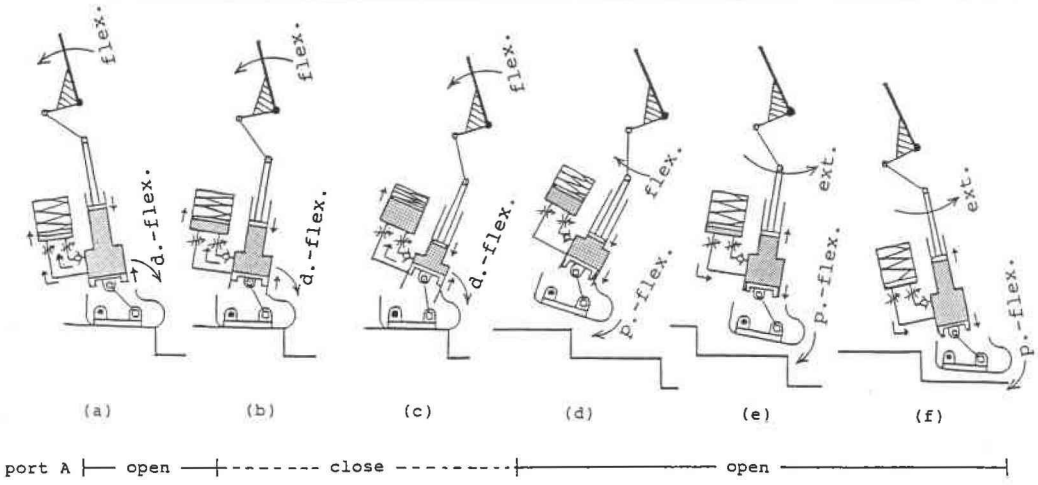


Fig 3. Top, sequential movement of the hydraulic system of the WLP-7R during level walking.

Fig. 4. Bottom, sequential movement of the hydraulic system of the WLP-7R during stairs descent.

(2) *Descending stairs*

The sequence for stairs' descent is basically the same as that of level walking described above. After the port B is closed the ankle joint and the knee joint mutually conterbalance (Fig. 4(b)) so that gradual yielding of the knee joint while sustaining full body weight is realized if the needle valve at the port A is adequately adjusted. Note that automatic stability of attitude, which will be particularly necessary for stairs' descent, is mechanically provided by this hydraulic interaction. For instance, an excessive flexion of the knee joint, which is assumed to occasionally happen, works to plantarflex the ankle joint. The moment of the plantarflexion adversely works to extend or "lock" the knee joint combined with extension moment of a hip joint, so that the excessive flexion of the knee joint will be automatically alleviated. After the sole lifts, the ankle joint starts to plantarflex by spring force, which leads to flexion of the knee joint so that the foot is able to step over the edge of the stairs (Fig. 4(d)). The knee joint starts to extend actively after the port B opens and the oil flows from the accumulator to the knee ankle cylinder (Fig. 4(e)).

Walking experiments by amputees

Walking experiments by an amputee wearing WLP-7R were performed to confirm the prescribed

functions of WLP-7R (Fig. 5). After training for about one hour, the amputee (22 years old male amputated at the middle of the left thigh) walked on the flat surface and walked up and down the stairs by reciprocal stepping with his sound leg and his amputated leg wearing the WLP-7R. The needle valve on the channel A was adjusted appropriately according to the amputee's instructions while training. On level walking, he claimed that the knee joint easily yielded if the needle valve was excessively opened, whereas he claimed that it was hard to advance his body forward if the needle valve was unduly closed. The rate of the knee yielding during descent of the stairs was mainly regulated also by the needle valve on the channel A, and by spring force in the accumulator. The amputee started the training to descend the stairs with the needle valve almost closed, so that the yielding rate of the knee was at a slow pace at first. However, the amputee made the yielding rate of the knee faster by gradually opening the needle valve as he accustomed himself to descending the stairs in the same way as a normal person. Finally the opening degree of the needle valve reached the same position as was appropriate for level walking, which means that the amputee could descend the stairs as well as walk on the flat surface with no change of the adjustment of the needle valve.

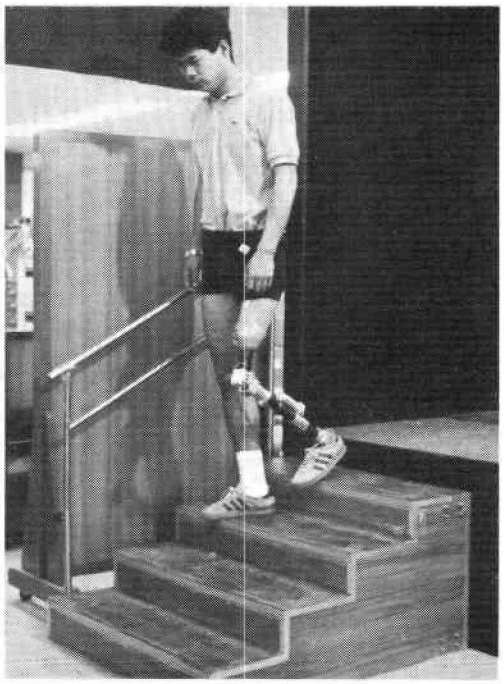


Fig. 5. Walking experiments with the WLP-7R (see text).

The results of the experiments of walking on a flat surface and of descending stairs are respectively shown in Figure 6 and Figure 7, in which the stick diagrams and the time courses of each joint of the amputee's lower limb wearing the WLP-7R are illustrated in the right columns, while the same results with a normal subject are shown in the left columns for comparison. One of the advantages derived by the proposed hydraulic system, which can be seen in Figure 6, is that the knee joint of WLP-7R was gradually yielding from single supported phase (S.S.P.), so that smooth changing from stance phase to swing phase was achieved. This performance of level walking was similarly shown in descending the stairs, (Fig. 7) that is the gradual yielding of the knee joint of the WLP-7R while sustaining full body weight.

The amputee also tried to ascend the stairs with the WLP-7R. The needle valve was almost closed for ascending stairs. Although active extension of the knee joint and plantarflexion of the ankle joint were impossible because no external actuator was installed, reciprocal ascending with both lower legs (sound and disabled) was achieved, since the mutual counterbalance between flexion of the knee joint and dorsiflexion of the ankle joint almost prevented the yielding (flexion) of the knee joint during the ankle joint's dorsiflexion.

Discussion

It was experimentally verified that a mutual counterbalance between flexion of the knee joint and dorsiflexion of the ankle joint is indispensable not only for descending/ascending stairs but also walking on a flat surface, this is physiologically supported by the fact that each extensor of a lower limb is mutually activated during stance phase. This is termed "homolateral extensor reflexion." Hydraulic power transmission is also necessary for a smooth change between walking phases. Gradual yielding of a knee joint and smooth progression to swing phase were then realized by the "conflict" between joints of the lower limb.

The weight of the WLP-7R (2.4 kg (5.3 lb)) is light enough to be used practically. Further refinement and testing are planned so that the design may be introduced into practical usage.

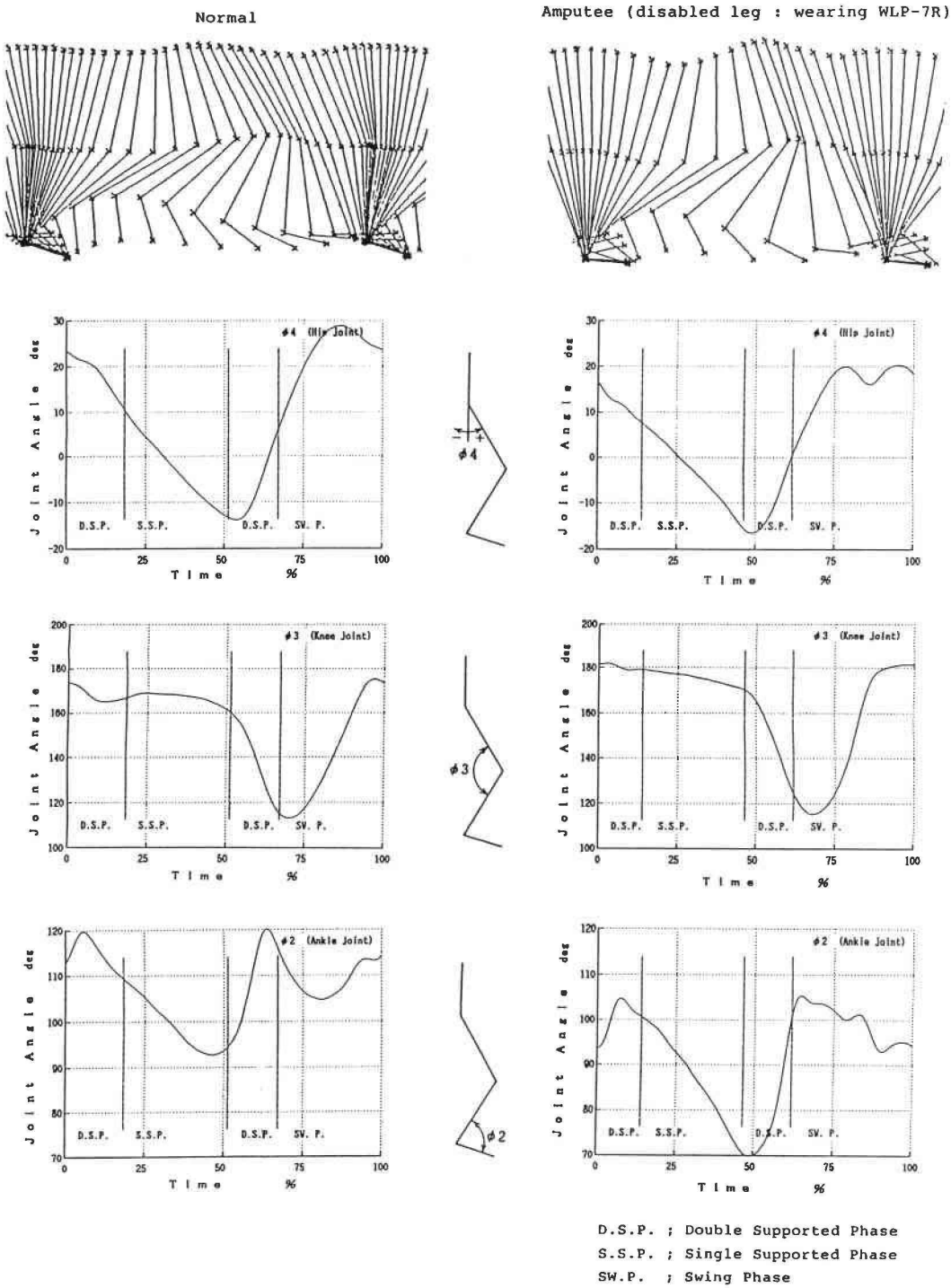


Fig. 6. Results of level walking experiments. The results for an amputee wearing the WLP-7R are shown in the right hand column with those for a normal on the left.

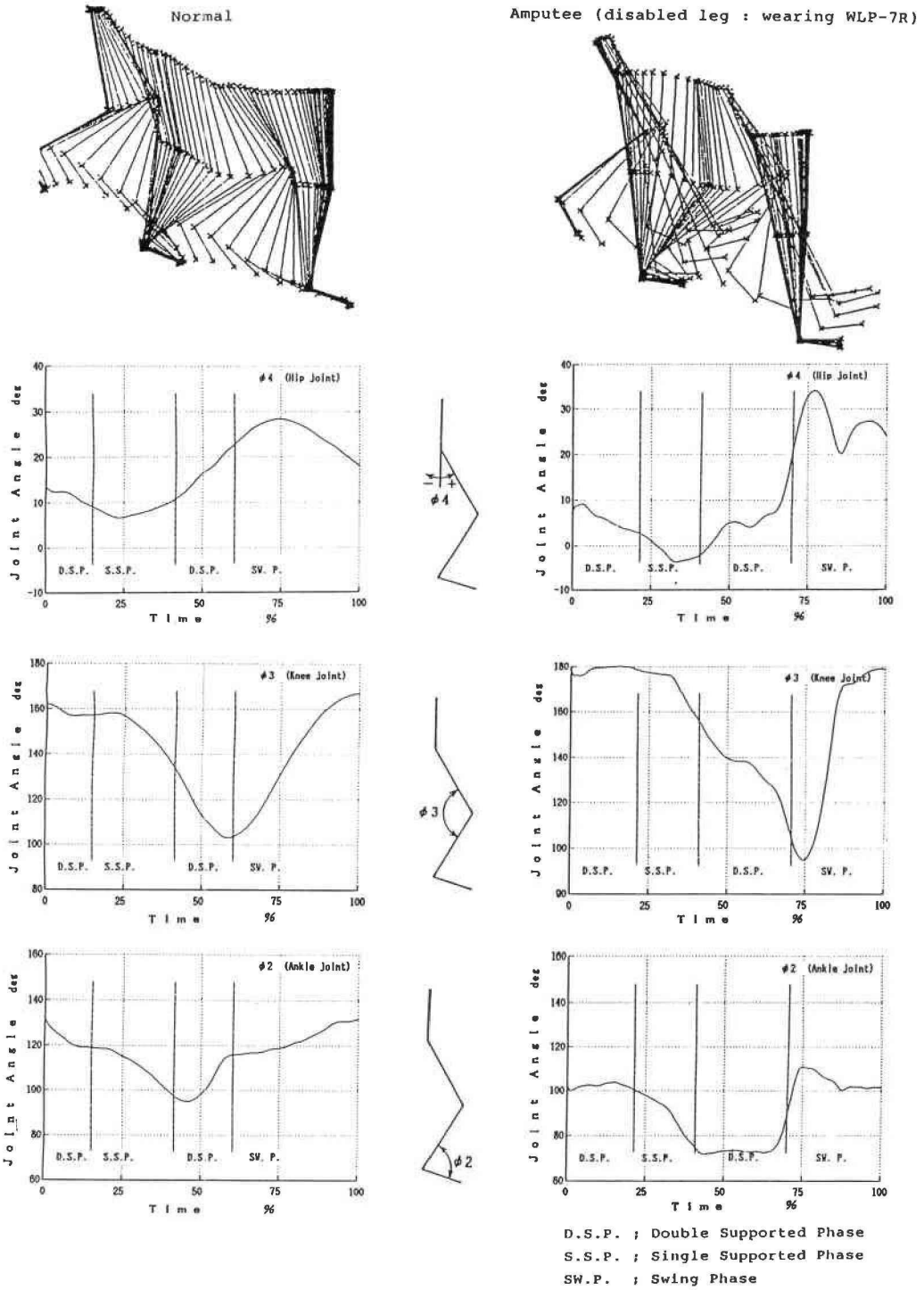


Fig. 7. Results of stairs descent experiments. The results for an amputee wearing the WLP-7R are shown in the right hand column with those for a normal on the left.

Acknowledgment

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