A NEW HYDRAULIC ABOVE KNEE PROSTHESIS FOR DESCENDING/ASCENDING STAIRS

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ABSTRACT

In our consecutive study new type of A/K prostheses which allow amputees to descend and ascend stairs with the same way as normal persons': reciprocal stepping with his normal and disabled lower limbs, have been developed and reformed. First, The necessity of counterbalance between flexion of a knee-joint and dorsiflexion of an ankle-joint in force (torque) is discussed based on the physiological evidences recently found concerning to interconnexion between ipsilateral muscles of a lower limb, which is "Homolateral extensor reflexion" modified by exteroceptive stimulation. A new hydraulic circuit which connects a knee-joint and ankle-joint in the same manner as the muscle-interconnexion of a normal lower limb, is then proposed. The WLP-7R (Waseda Leg Prosthesis-7 Refined) and its reformed version WLP-7R II both mounted the proposed hydraulic mechanism were constructed to put them to the walking experiments by amputees. The rasults of the experiments of walking on the flat surface and descending/ascending the stairs by the amputee wearing WLP-7R and WLP-7R II verified the validity and the necessity of the proposed hydraulic mechanism.

KEYWORD: A/K prosthesis, Descending/Ascending stairs, Hydraulic-actuation, Self-energized system, Automatic dorsiflexion.

I INTRODUCTION

As Mauch once noted, a knee-jont of an A/K prosthesis should have three control modes of the bending resistance (Mauch, H.A., 1967). One is for "the moderate bending resistance" for a swing-phase. The second is a significantly higher bending resistance to produce a moderate yielding rate under the full weight of an amputee, and the last state is a full lock-mode. There have been a few approach to realize the second mode to descend stairs and to alternate these modes automatically during walking (Mauch, 1968 ; Horn, 1972). In the "HYDRAULIC S-N-S knee-unit" developed by Mauch, the gradual yielding of the knee-joint was accomplished by some grooves caved on the side of the piston to leak the oil between both chambers in the cylinder during a stance-phase. The most fatal problem of this system exists in the mechanism of switching the modes from a stance-phase to a swing-phase (unlocking the knee-joint) for which amputees had to hold "hyperextension" at the end of a stance-phase. There was the same problem in the A/K prosthesis developed by Horn, in which the knee-joint could lock at any flexion-angle by the ratchet mechanism. The unlocking of the knee-joint also required hyperextension, which caused unnatural attitude and high energy consumption of the amputees. These instances explicitly indicated that the rigidity of a knee-joint must change continuously not suddenly.

We also confirmed dynamically and physiologically that an ankle-joint takes a significant role for walking especially for descending /ascending stairs. It can be said that the rigidity of a knee-joint and its smooth changing are qualitative assets derived from quantitative counter-balance between plantarflexion-torque of an ankle-joint and extension-torque of an knee-joint. The success of ascending stairs by the Horn's A/K prosthesis was much due to the damping mechanism of the ankle-joint.

In our formerly developed "Multifunctional A/K prosthesis" named WLP-7, we proposed a new type of hydraulic mechanism in which the knee-cylinder, the ankle-cylinder and the accumulator were hydraulically connected to acquire high but gradually changing rigidity of the knee-joint during a stance-phase (Koganezawa, et al.,1987), while assuring a body-stability of a single supported phase especially during descending/ascending stairs. WLP-7 also had an automatic regulator of the rigidity of the knee-joint to adapt walking pace, which is actuated by the DC-motor and controlled by the micro-computer. While, the basic walking pattern was realized only by the hydraulic mechanism so that we next constructed the refined and simplified model WLP-7R and WLP-7R II successively: they can both enable an amputee to descend/ascend stairs with reciprocal stepping by both disabled and normal lower limbs, as well as to walk on a flat surface with no external power source nor electric instrument, although they do not have the function for adapting walking pace. One function added into the WLP-7R II in addition to the functions of the WLP-7R was the "automatic dorsiflexion " of the ankle-joint during a swing phase to improve the asymmetric body-pitch during walking on a flat surface.

II HOMOLATERAL EXTENSOR REFLEXION

It is well known that an afferent motor neuron activated by extensor-reflexion of one extensor of a lower limb generally effects any other extensors of a ipsilateral limb and relaxes all flexors of the contralateral limb (Eccles, R.M. et al., 1958; Jankowska, E. et al., 1967(a)(b)). Especially it should be noted that the extension of a M. triceps surae also brings the extension of the ipsilateral M. quadriceps femoris, while the inhibition caused Ib afferent of the M.triceps surae, which might relaxes the M.quadriceps and buckles the knee-joint, "disinhibited" by the proprioceptive afferent distributed on a heel-sole (N.Sularis) (see Fig.1 (b)), so that the contraction of the whole ipsilateral extensors continues during a whole stance phase (Deseilligny, E.P. et al., 1982). In the kinematical point of view, this mutual effect of ipsilateral extensors will be able to be translated like that the damping force of the dorsiflexion of an ankle joint (generated by a M. triceps surae) also extend a knee joint (by contracting a M.quadriceps femoris). Furthermore, at the end of the stance-phase, the inhibition due to the Ib afferent from M.triceps begins to be in effect with facilitation which is brought by a proprioceptive stimulation on a toe-sole (Fig.1 (c)) so that the M.quadriceps begin to relax for gradual yielding of the knee-joint and for smooth transferring to the swing-phase. The multifunctional A/K prosthesis : the WLP-7R and the WLP-7R II developed in this study have a hydraulic mechanism of which fundamental principles and working are identical to the moto-physiological interaction between extensors, called Homolateral extensor reflexion modified by proprioceptive stimulation of a sole, mentioned above.

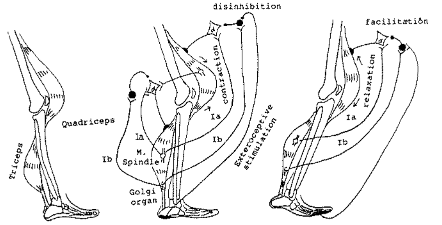


Fig. 1 Motor-newronal circuit and its sequential activity during a stance-phase based Deseilligny's study.

III MULTIFUNCTIONAL A/K PROSTHESIS WLP-7R

Fig. 2 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 mentioned in the former section. The port B is closed by the ankle-piston as the ankle joint dorsiflexes during a stance-phase. Thereafter sudden buckling of the knee joint is prevented by hydraulic pressure which effects 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 Fig. 3. The structural material of the WLP-7R is CFRP (Carbon Fiber Reinforced Plastic; black part of the shank in Fig. 3) and duralumin. The weight of the WLP-7R under the knee-joint is 2.4 Kg which is approximately as same as of a conventional A/K prosthesis.

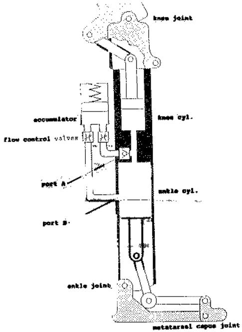


Fig. 2 Schematic drawing of the main structure and hydraulic circuit of the WLP-7R.

Fig. 3 Appearance of the WLP-7R.

IV THE SEQUENCE OF THE MECHANISM DURING WALKING

(1) Level walking.

Fig. 4 shows the successive movements of the mechanical parts of the WLP-7R. Let us starts from a timing of sole-contact (Fig. 4(a)). The port B is sequentially closed by the ankle-piston as dorsiflexion is progressing and the ankle-piston is pushed up during a stance phase. Hereafter dorsiflexion of the ankle-joint hydraulically pushes the knee-piston upward so that the rapid yielding of the knee joint is prevented (Fig. 4(b)). At the same time oil gradually flows into the accumulator via port A of which 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 phases from a stance to a swing is smoothly performed (Fig. 4(c)). The following sequence is consecutively performed after a swing phase starts. The knee-joint

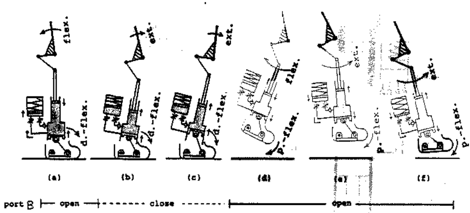


Fig. 4 Sequence of the hydraulic system of the WLP-7R (level walking).

begins to flex. → The knee-piston is pushed down. → The ankle-pistonis pushed down (Fig. 4(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. 4(e)). → The next sole contact comes (Fig. 4(f)).

(2) Stairs' descending.

The sequence for stairs' descending is basically identical to of level walking described above. After the port B is closed the ankle-joint and the knee-joint is mutually counterbalance (Fig. 5 (b)) so that gradual yielding of the knee-joint while sustaining a 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 remarkably necessary for stairs' descending, is mechanically realized by this hydraulic interaction. For instance, an excessive flexion of a knee-joint, which is supposed to occasionally happen, works to plantarflex an ankle joint. The moment of the plantarflexion adversely works to extend or "lock" the knee-joint combined with extention-moment of a hip-joint, so that the excessive flexion of the knee-joint will be automatically alleviated by the mechanical feedback effect. After the sole lifts, the ankle-joint starts to plantarflex by spring force, which leads flexion of the knee-joint so that the foot is able to step over a hedge of stairs (Fig. 5(d)). The knee-joint starts to extend actively after the port B op:ns and the oil flows from the accumulator to the knee-ankle cylinder (Fig. 5(e)).

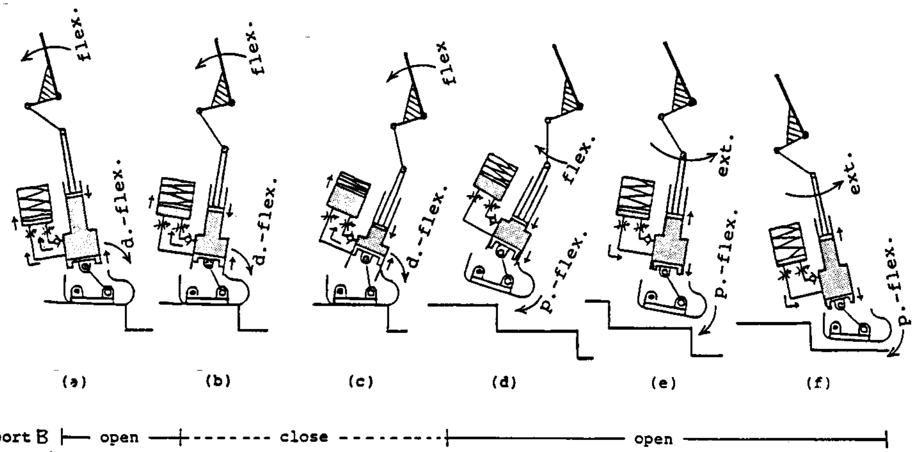


Fig. 5 Sequence of the hydraulic system of the WLP-7R (stairs' descending).

V WALKING EXPERIMENTS OF THE WLP-7R BY AMPUTEES

The walking experiments by an amputee wearing WLP-7R was performed to confirm the prescribed functions of WLP-7R (see Fig. 6). After a 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

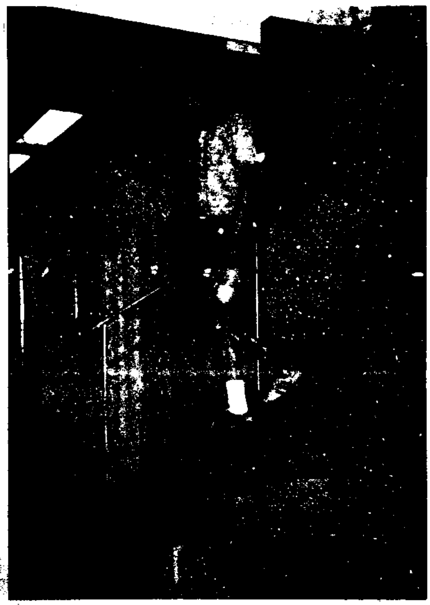


Fig. 6 Experiment of the WLP-7R by the amputee.

designation while training. On level walking, he claimed that the knee-joint was easily yielded if the needle valve was excessively opened, whereas he claimed to be hard to advance his body forward if the needle-valve is unduly closed. The rate of the knee-yielding during descending the stairs was mainly regulated also by the needle-valve on the channel A, but by spring-force in the accumulator. The amputee started the training of descending the stairs with a state of almost closing of the needle-valve, 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 being faster by gradually opening the needle-valve as he accustomed himself to descending the stairs with the same way as the normal persons', finally the opening degree of the needle valve reached to be same as the appropriate degree on level walking, which means that the amputee could descend the stairs as well as walk on the flat surface with no adjustment of the needle-valve.

The results of the experiments of walking on a flat surface and of descending stairs are respectively shown in Fig.7 and Fig.8, in which the stick-diagrams and the time-courses of each joint of the amputee's lower limb wearing the WLP-7R are illustrated at right columns, while the same results with a normal subject are shown at the left columns for comparison. One of the advantages derived by the proposed hydraulic system, which can be seen in Fig.6, is that the knee-joint of WLP-7R was gradually yielding from single-supported phase (S.S.P.), so that smooth changing from a stance-phase to the next swing-phase was acquired. This performances of level walking was similarly shown in descending the stairs, which is found in Fig.8, 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 (not perfectly closed) in case of ascending stairs. Although active extension of the knee-joint and plantarflexion of the ankle-joint were impossible because of installing no external actuator, reciprocal ascending with both lower legs (sound and disabled) was realized, since the mutual counterbalance between flexion of the knee-joint and dorsi-flexion of the ankle-joint almost prevented the yielding (flexion) of the knee-joint during ankle-joint's dorsiflexing.

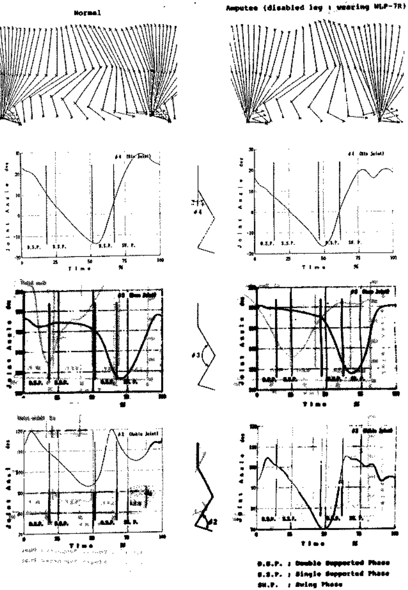


Fig. 7 Stick diagrams and the time cources of each joint of the lower limb of the amputee wearing WLP-7R (right column) during the level walking. Those of the typical normal subject are shown in the left column for comparison.

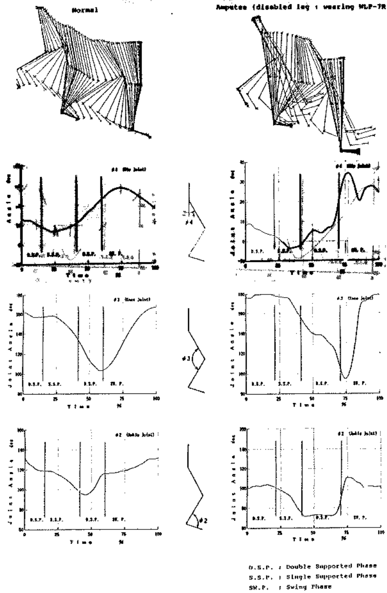


Fig.8 Stick diagrams and the time cources of each joint of the lower limb of the amputee wearing WLP-7R (right column) during descending the stairs. Those of the typical normal subject are shown in the left column for comparison.

Ⅵ MULTIFUNCTIONAL A/K PROSTHESIS: WLP-7R Ⅱ

(1) Automatic dorsiflexion

There was one problem in the WLP-7R, which inevitably brought from the fundamental mechanism of the WLP-7R. The ankle-joint plantar-flexed during a swing-phase to realize the free swing of the shank since the flexion of the knee-joint was performed according to the plantarflexion of the ankle-joint when the port B (see Fig.2) closed. The plantarflexion of the ankle-joint during a swing-phase caused the toe being apt to scratch on a floor so that the amputee walked with lifting the body a little during the prosthesis's swing-phase so as not to get the toe touch on the floor.

In the WLP-7R Ⅱ, this disadvantage was overcome by introducing the new mechanism : "Automatic dorsiflexion" of the ankle-joint. The assembly of the foot-part is illustrated and showed in Fig.9. The movements of this mechanism during walking are sequentially illustrated in Fig.10. The joint B fixed to the shank gets down to the bottom of the curved groove by the amputee's weight at the beginning of a stance-phase (Fig.10 (a)→(b)). The joint B is locked by the ratchet as far as dorsiflexing continues during a stance-phase (Fig.10(c)→(d)). At the next swing-phase, the following sequential movements are successively performed. The ankle-joint begins to

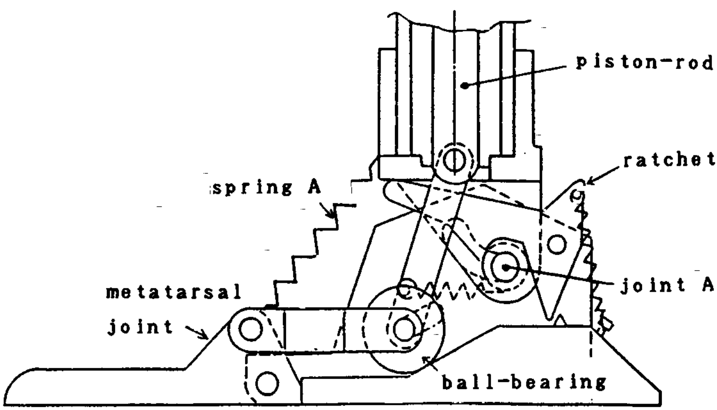


Fig.9 The foot-part of the WLP-7R Ⅱ with the mechanism of the "automatic dorsiflexion".

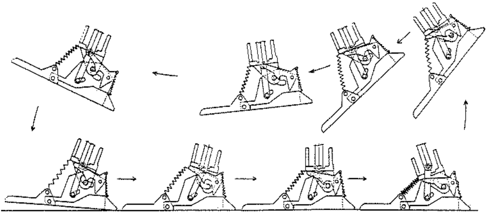


Fig. 10 Movement of the "automatic dorsiflexion" while walking on a flat surface.

plantarflex accompanying to the flexion of the knee-joint (Fig. 10(e)). → The ratchet is unlocked and the joint B slides along the curved groove (Fig. 10 (f)). → The ankle-joint plantarflexes due to the tension of the spring A (Fig. 10(g) → (h)).

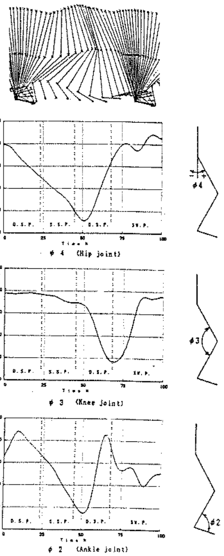
(2) WLP-7R II

The appearance of the WLP-7R II is shown in Fig. 11. Almost all mechanisms and functions are identical to the WLP-7R except the foot-part mentioned above. The weight was about 2.2 Kg; 0.2 Kg lighter than the WLP-7R.

VII WALKING EXPERIMENTS OF THE WLP-7R II BY AMPUTEE

The procedures of the walking experiments were as same as those of the WLP-7R. The same amputee participated as a subject. Only the results of walking on the flat

Fig. 11 Appearance of the WLP-7R II



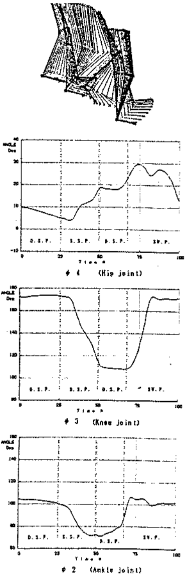


Fig.12 Stick diagram and the time courses of each joint of the lower limb of the amputee wearing the WLP-7RⅡ during level-walking.

Fig.13 Stick diagram and the time courses of each joint of the lower limb of the amputee wearing the WLP-7RⅡ during descending the stairs.

surface, descending the stairs and also ascending the stairs were illustrated in Fig.12, 13 and 14 respectively. It can be found in Fig.12, the bottom right graph, that the automatic dorsiflexion was performed during the swing-phase. Also it can be seen that the knee-joint extended even atthe single supported phase of ascending the stairs (Fig.14, the middle right graph), which is a success due to the hydraulic counterbalance between the ankle- and knee-joint.

VII DISCUSSION

It was experimentally verified that a mutual counterbalance between flexion of a knee-joint and dorsiflexion of an ankle-joint is indispensable not only for descending/ascending stairs but also walking on a flat surface, which was physiologically supported by the fact that each extensor of a lower limb is mutually activated during a stance phase, that is called "Homolateral extensor reflexion" modified by proprio-ceptive stimulation from a sole during a stance-phase to acquire smooth changing of walking phases.

Hydraulic power transmission is also necessary to realize this smooth changing from stance to swing. Gradual yielding of a knee-

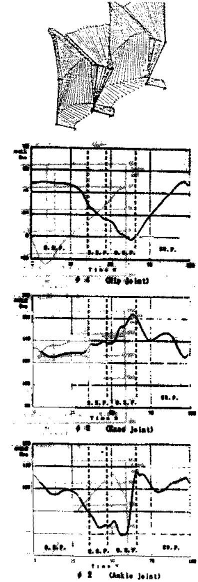


Fig.14 Stick diagramand the time cources of each joint of the lower limb of the amputee wearing the WLP-7R II during ascending the stairs.

joint and smooth progression to a swing phase were then acquired as the qualitative assets of the "conflict" between joints of a lower limb.

The weight of the WLP-7R II (2.4 Kg (5.3 lb)) is light enough to be used it practically. So we are now planning further refinement and testing for serving it into practical usage.

Acknowledgment

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