DEVELOPMENT OF AN ABOVE-KNEE PROSTHESIS FOR WALKING STAIRS

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ABSTRACT

An attempt to develop a new multifunctional above-knee prosthesis and walking experiments with amputees are presented in this paper. This new prosthesis, named WLP-8RII (Waseda Leg Prosthesis, version 8 Refined mark II) contains the new Electric/Hydraulic Hybrid Actuator. This actuator is composed from two power assemblies, the electric power and the hydraulic power assembly, for two tasks:

1) a generation of powerful enough torque by a DC-motor to extend the knee joint against the gravity, and

2) a variable extension torque at the knee joint at swing phase.

The weight of the knee joint of the WLP-8RII and the battery is 3.9 kg and 3.2 kg respectively. Two above-knee amputees wearing this prosthesis could walk on a level floor with various gait cycles (1.07 to 1.42 sec) and climb the stairs with natural posture like the normal persons.

KEY WORDS: Above-knee prosthesis, stairs walking, electric/hydraulic hybrid actuator, variable gait cycles

INTRODUCTION

Above-knee (A/K) prostheses are used for gait restoration of A/K amputees. Currently used A/K prostheses doesn't respond to needs of daily living activities of many amputees. All currently used prosthesis were designed only for level walking. Amputees, when required, are climbing stirs with an unnatural posture. In many existing devices, it is impossible to adjust the stiffness of the knee joint motion during the swing phase of the gait cycle. Speed adaptation of amputees requires high energy consumption and complete asymmetry of the gait, and often it is not possible.

To solve these two requirements, we developed several prototypes of A/K prosthesis:

1) WLP-7 in 1985 [1,2], which changes the stiffness of the knee joint motion,
2) WLP-8R in 1987 [3], which has features suitable for staircase climbing.

In this study, we developed the WLP-8RII which combines both of above mentioned functions and performed clinical tests in A/K amputees.

MECHANISM OF THE WLP-8RII

We will describe the newly developed hydraulic/electric hybrid actuator which is capable to provide knee extension under full bodyweight bearing and controlled swing of the prosthesis.

1.Hydraulic/electric hybrid actuator

As said, the unit is composed of two power assemblies, the electric power assembly and hydraulic power assembly. The action of each power assemblies is presented in Table 1.

For the gait on a level ground and descending the staircase, an amputee can walk only with the hydraulic power assembly. The electric power assembly adjusts the extension torque generated by a spring at the knee joint during the ground level walking. While to ascending the staircase, the combined power effect is used. During the stance phase, the hydraulic power and the electric power provide the prosthetic knee extension, and push up of the upper body. During the swing phase, the electric power assembly controls the prosthesis behaviour.

	Walking on a level floor	Descending the stairs	Ascending the stairs
Electrical power assembly	adjust the stiffness of the knee joint		Supplements the power to the knee joint
Hidraulic power assembly	realizes the sequential movements of walking		

Table 1. Action of the hydraulic/electric power actuator

a.Hydraulic power assembly

Figure 1 illustrates the basic structure and the mechanism of the WLP-8RII. The hydraulic power assembly is located at the lower part of the shank. The contraction of the hydraulic circuit is similar to the one described in WLP-7R [2 - 4]. During the stance phase, the oil in the knee cylinder and ankle cylinder is pushed out to the accumulator (knee flexion and ankle dorsiflexion). During the following swing phase, reciprocical process occurs as a result of the loaded spring mechanism.

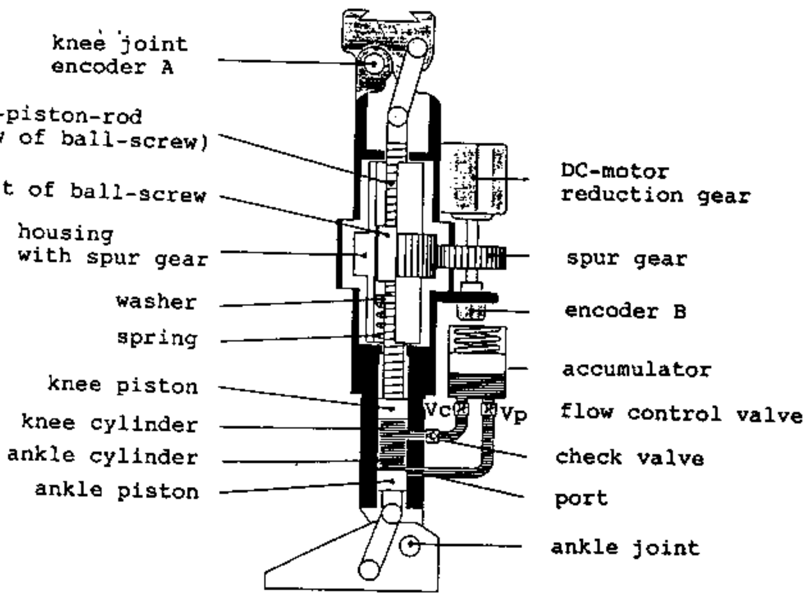


Figure 1. The basic structure of the WLP-8RII

The ankle cylinder is connected, directly, with the knee cylinder, in such a way that knee flexion and dorsiflexion counterbalance mutually.

The post of the ankle cylinder is closed, when the shank bends forward and pushes up the ankle mechanism piston in the stance phase. The flow control valve V_C was manually adjusted before. The dorsiflexion of the ankle joint prevents the sudden and uncontrolled knee flexion, after the port is closed. This mechanism realizes the neuro-muscular mechanism called homolateral extension reflex.

The oil flow into the accumulator is controlled (check valve). The flow back in both cylinders is prevented with the same check valve. After the port is opened, during the following swing phase, the oil flows to both cylinders.

b.Electric power assembly

The electric power assembly is mounted in the upper part of the shank. The torque generated by a DC-motor is transmitted to a housing via a reduction gear and the spur gear, then transformed to the force pushing up the knee-piston-rod by the ball screws.

The electric power should be supplemented to the knee mechanism in different phases of the gait. When climbing the stairs, power for push up is needed. For ground level gait controlled flexion during the swing phase is required. The role of the electric power assembly, during level walking, is to adjust the stiffness of the knee joint (see Table 1). The friction of the electric power assembly should not disturb the passive movement of the hydraulic assembly.

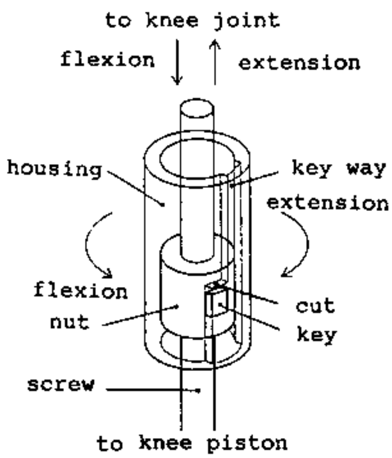


Figure 2. Electric power assembly

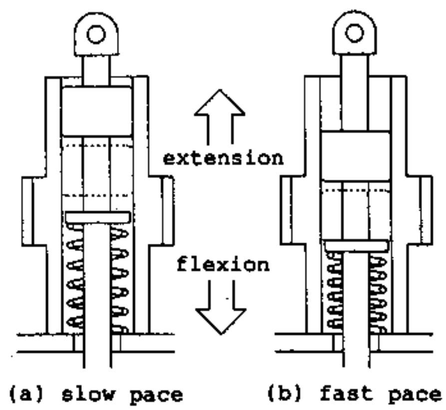


Figure 3. The stiffness control mechanism at the knee joint of WLP-8RII

Figure 2. shows the details of the mechanism of the electric power assembly. The electric power is transmitted through a "key" mounted at the housing of the ball-nut. During the process, of up-stairs walking, the assembly rotates the housing and the nut, thus the force is generated at the knee-piston-rod (screw). The screw is pushed up during this process (Figure 2). For the flexion the housing is rotated in opposite direction, thus the key meshes with the cut at the ball-nut, and the screw is pulled down. This pull-down is followed by an immediate knee joint flexion. When walking on a flat floor or descending stairs the nut is set at the upper part of the screw. This decreases the friction, i.e. the passive movement of the hydraulic power assembly is enabled. The slit in the construction enables fast movement of the key.

c.Mechanism for stiffness control of the knee joint

A spring mechanism is mounted below the nut of the ball-screw (Figure 1). In flexion of the knee, the nut moves down and the spring is shortened. The force will be generated in spring, tending to extend the knee joint. Figure 3 shows that the stiffness can be adjusted by pre-loading of the spring. For the slow rate of the gait the spring will not be compressed (Figure 3a). For the fast rate of the gait, the nut will be adjusted to the lower part of the nut. This position produces the higher compression spring loading. The initial compression loading decreases the joint terminal flexion angle. This allows the amputee to walk faster. The information from the encoder B (Figure 1) triggers a DC-motor.

SEQUENCES IN THE GAIT WHEN WLP-8RII IS USED

The level walking, stairs ascending and descending with WLP-8RII prosthesis are described in this paper.

a.Ground level walking

Figures 4a and 4b show the slow and fast rate walking, respectively.

During the stance phase:

(1) Heel contacts the floor with the knee joint extended. When the WLP-8RII sustains the load of upper body, the knee bounces (limited knee joint flexion). The shank bends forward and the oil is pushed out from the both joint cylinders to the accumulator.

(2) The shank keeps bending forward and this closes the port of the accumulator.

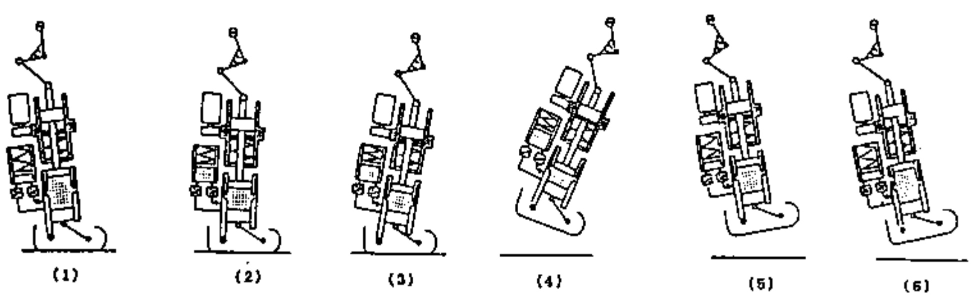
(3) The oil flowed from both joint cylinders should pass through the check valve and the control valve V_C. The V_C is adjusted to almost closed position. This adjustment provides that a dorsiflexion of the ankle joint prevents the knee joint flexion. The dorsiflexion generates the extension torque, preventing uncontrolled, sudden, knee flexion.

During the swing phase:

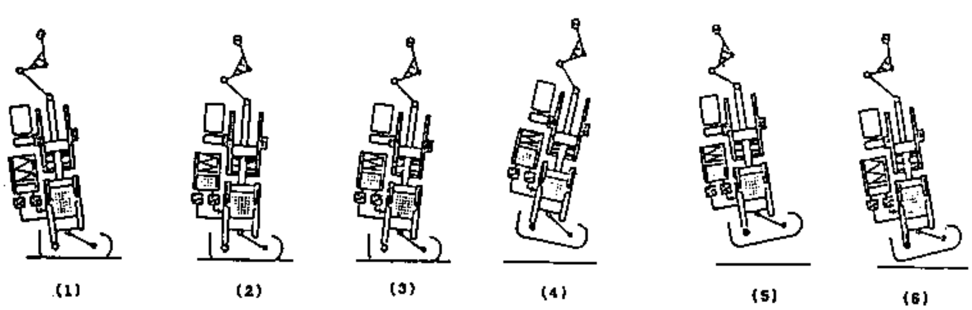
(4) After the toes are pulled up form the floor, the hip flexion produces inertial forces tending to flex the knee joint. The flexion of the knee joint pushes down the ankle piston.

(5) After the port is opened,

(6) the spring mounted in the accumulator begins to push out the oil into the both joint cylinders.



a. slow walking



b. fast walking

Figure 4. Sequences during the gait on a ground floor

In case of slow walking, the nut is set at the upper part of the screw. The braking torque generated with the spring is effective at the phase (4) showed in Figure 4a. In the fast walking case, the nut is set at the lower part of the screw. The braking torque affects the knee motion (Figure 4b) preventing the knee to flex to much and providing faster knee extension.

b.Ascending the stairs

Figure 5. shows the successive phases in ascending the staircase. The controlling method for the electric power assembly is described.

At the stance phase:

(1) The toes contact with the step occurs with the flexed prosthesis. After the sole contact, the shank bends forward. The ankle piston is pushed up, and the oil is pushed to the accumulator.

(2) The shank bends forward little more, and the port of the accumulator becomes closed. As said, the V_C is adjusted almost closed, and the dorsiflexion and knee extension occur.

(3) At this phase, the electric power is supplemented. The extension of the knee joint results from both power assemblies, and boosts up the upper body. The essential parameter for natural posture walking is the timing of the electrical assembly. The timing is obtained with the sensory feedback. Sensory information, for the initiation of the DC-motor, comes when the prosthesis is fully loaded and the amputee tries to extend the affected side hip joint. The controller, using 8 bits single-chip microcomputer, receives the information from the encoder A (Figure 1). The threshold value is determined in clinical walking experiments.

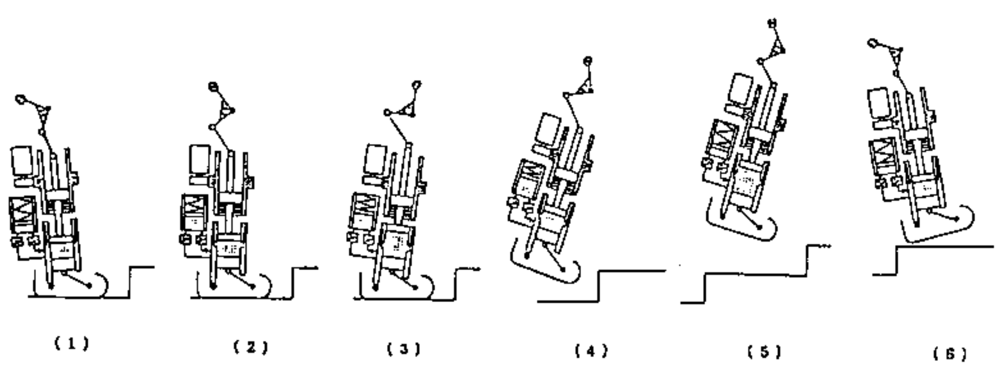


Figure 5. Sequences during ascending the staircase

At the swing phase:

(4) After the sound leg reaches the next stair's step, the WLP-8RII is lifted. The controller detects this through the foot switch placed at the sole. Control command initiates the knee flexion, using the electric power assembly.

(5) The knee joint is flexed (external control) during the hip flexion (voluntary control of the stump). This opens the accumulator port and the oil is pushed in both joint cylinders.

(6)The terminal knee flexion is limited to about 60° with a DC motor. This angle can be changed.

c.Descending the staircase

Figure 6 shows the successive movements in descending the staircase. These movements are basically the same as ground level walking.

At the stance phase:

(1) Heel contacts the floor with the extended leg.

(2) The knee flexion and the ankle dorsiflexion occur, resulting with the closure of the port to the accumulator.

(3)The oil is flowing slowly, providing more dorsiflexion and controlled knee flexion. This is a slow process giving stable support to the amputee throughout the moment he reaches the next step with the sound leg (toe contact !).

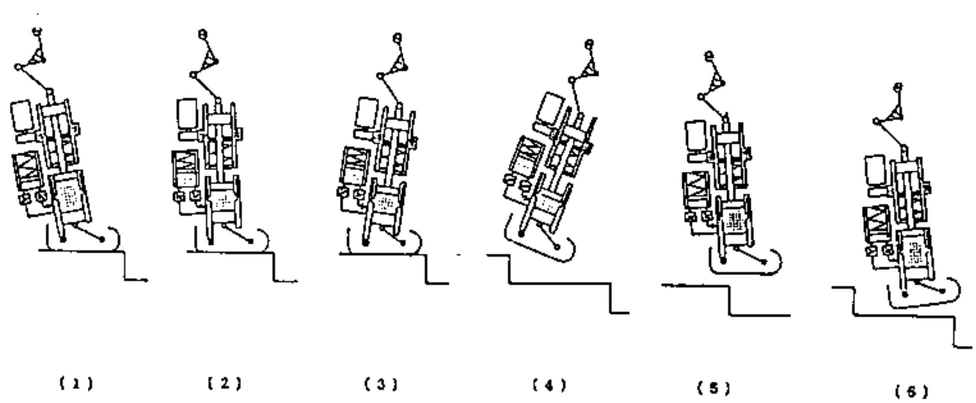


Figure 6. Sequences in descending the staircase

At the swing phase:

(4) While the amputee swing the thigh forward, the knee joint is flexed and pushes down the ankle piston.

(5) After the port is opened,

(6) the oil is pushed into the both joint cylinders.

WALKING EXPERIMENTS

Two A/K amputees, aged 24 and 26 were included in clinical trials. Both amputation were in the middle third of the thigh. Figure 7 shows the walking experiment on the stairs. The battery and electronic circuitry were mounted in the patients back-pack.

The joint trajectories and the stick diagram during the gait of this subject are presented in Figures 8 to 11. Analog data were digitized, with an opto-electrical digitizer. Sampling frequency was 50 Hz.

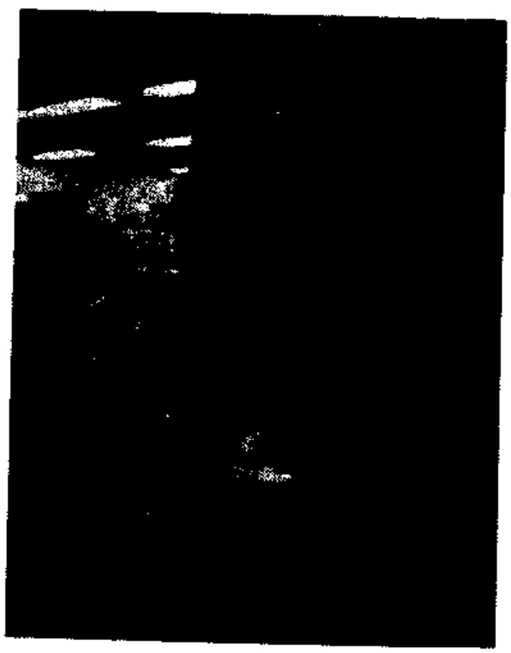


Figure 7. Walking with the WLP-8RII A/K prosthesis

a.Level walking

As described, the nut was set at lower part of the screw (fast rate walking). The amputee was asked to walk at a most convenient speed. Later, the nut was moved to the upper part of the screw, and amputee repeated the gait.

We compared the same speed performance with different positions of the nut. With the nut set at the upper part the amputee should walk as fast as possible, and than, he was asked to keep the same speed with the nut moved lower.

Gait cycles, at fast and slow walking, were 1.43 s (Ca =84) and 1.07 s (Ca = 112), respectively.

The results of slow walking (the nut at the upper part) are at the right end of the Figure 8. The trajectories recorded in normal person are at the left side.

Period (1) and (3) are double support phase, period (2) is the single support phase and period (4) is a swing phase.

The hip joint of the amputee extends little more in the middle part of the swing phase. This movement appears, commonly, among the amputees wearing different A/K prostheses. As presented in Figure 8, the beginning of flexion is synchronized with the hyperextension of the knee joint. It is assumed that this hip flexion is caused by the angular momentum of the thigh.

The knee movement is found to match the movement if a normal subject in our experiments. These movements contributed the shock absorbtion at the heel strike. The knee was found to be slightly bend, also, at the end of the single support phase.

Results of the stiffness control (positioning of the ball-nut) are presented in Figure 9.The dashed line presents the trajectory with the nut positioned lower, and the full line the upper position of the nut.

When the nut was positioned at the upper part of the screw (adjusted for slow walking) the extension angle of the hip joint was -10°, while it reached -15° for the ball-nut positioned for the fast rate of the gait. The swing of the leg was much faster when the fast gait was performed. The knee joint began to flex at the middle phase of the double support phase. The forward movement of the thigh was responsible for the quick swing motion. In normal gait speed the knee joint flexion was larger, i.e. the swing phase was extended.

b.Ascending the staircase

The flow control valve V_c was set closed to sustain the load during weight bearing phase with the hydraulic power assembly. The threshold value (the knee bounce terminal flexion) of the knee joint was determined which starts the DC-motor action, as described. The threshold angle was about 5° and the amputee could ascend the stairs without hand supports. The training period for the use of this system was 1 hour. The ascending performance is presented in Figure 10.

At the beginning of the stance phase, the hip angle didn't change, although a knee joint flexed gradually. It was assumed that at this phase WLP-8RII prosthesis supports the body.

The extension of the hip joint generated the knee joint to extend a little and DC-motor started the extension. Even at the single support phase, the knee joint extended providing push up of the upper body because of combined action of electro/hydraulic actuator. During the swing phase the knee joint started flexing immediately, due to the special construction of the motor unit.

The toe cleared the step like in the gait of normal subject (stick diagram).

c.Descending the staircase

The ball-nut was set at the top of the screw, and the key could move along the slit without shortening the spring. The flow control valve V_c was adjusted to walk easily and stable at the ground level.

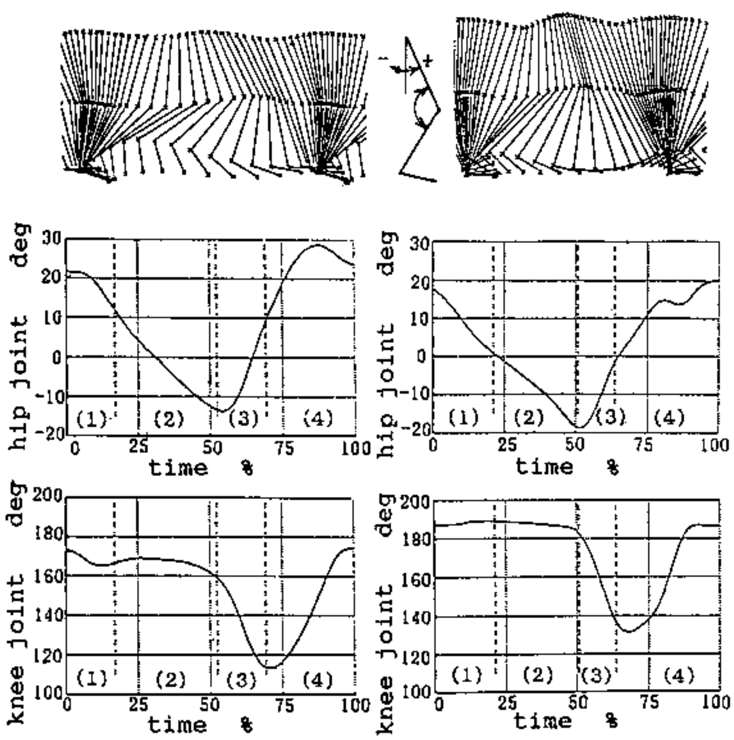


Figure 8. Results of the ground level walking

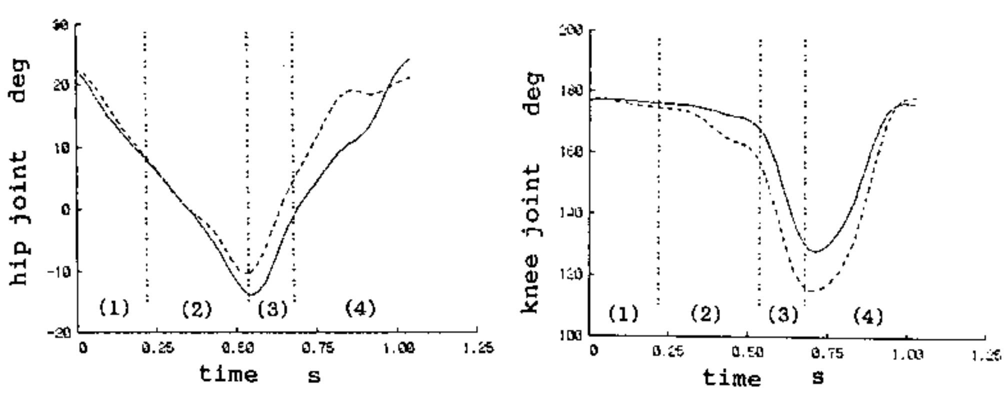


Figure 9. Results of the slow and fast rate walking

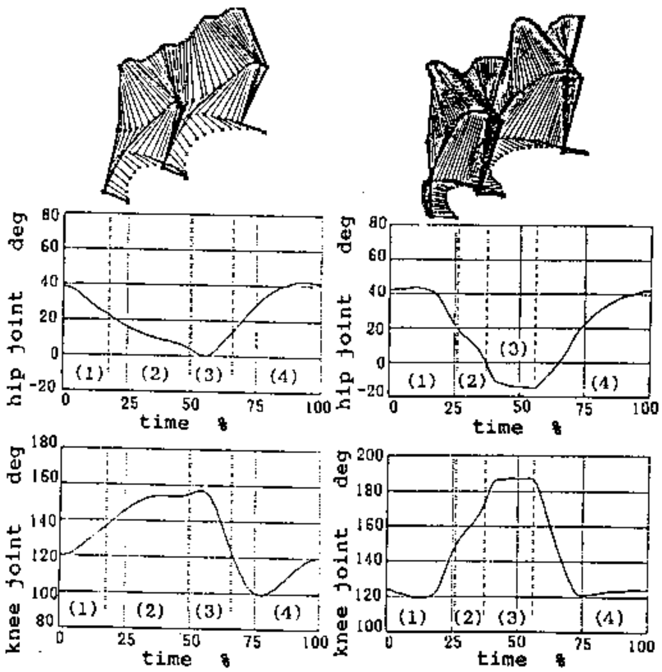


Figure 10. Results on the use of WLP-8RII when ascending the staircase

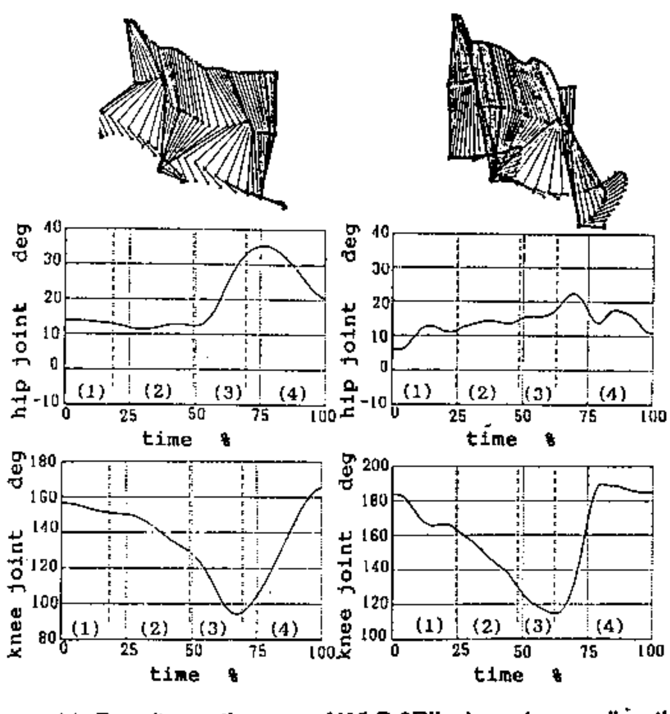


Figure 11. Results on the use of WLP-8RII when descending the staircase

Both subjects could descend the staircase after the training of about 30 minutes. Results are presented in Figure 11. The hip joint flexed like in the normal gait. The knee joint kept flexing, when supporting the body, like in the normal subject at stairs. At the swing phase, the knee joint was extended quickly enough for the heel contact with succeeding stair.

CONCLUSION

We designed and tested the new prototype of the above-knee prosthesis for variable speed on ground level and stairs walking. The A/K prosthesis is equipped with an actuator which combines electric and hydraulic assemblies. These assemblies were designed according our experience with earlier version of WLP-7 and WLP-8 prostheses. The mass of under knee mechanism and batteries, in this case, were 3.9 kg and 3.2 kg respectively.

This prosthesis allows the variable gait cycle between 1.07 and 1.43 sec. This property is provided with adjustable stiffness of the knee joint.

Clinical tests, in two subjects, proved the applicability of WLP-8RII for ascending and descending, without hand supports, similar to the normal person.

Acknowledgement: The walking experiments were performed at KANAGAWA SOUGOU REHABILITATION CENTER with much kindness of Mr. Y. Ehara and other members of the staff.

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