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A DEVELOPMENT OF A/K PROSTHESIS ADAPTABLE TO VOLUNTARY WALKING PERIOD

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Summary

In order to develop an A/K(Above-Knee) prosthesis adaptable to a voluntary walking period on a level walking, the dynamical analysis during a swing phase was performed, in which it was confirmed the damping moment around the knee-joint should be variable for walking with voluntary walking period, and moreover a little driving moment was necessary for fast walking. Hence the A/K prosthesis model WLP-6 (Waseda Leg Prosthesis-6) being able to regulate its damping coefficient according to an amputee's voluntary walking period, and being able to generate a little driving moment without any power sources, was developed. In order to perform an amputee's voluntary control, EMG (Electro-Myo-Gram) data composition algorithm and the prediction algorithm for the next step's walking period were proposed and assembled into the control unit based on one chip micro-computer. The whole system was examined on the walking experiment, in which it was confirmed that the amputees could voluntarily walk with WLP-6 in the range of the walking period; 1.1～1.6[sec].

1 Introduction

An A/K prosthesis that has already been in use are not enable to regulate the moment around the knee-joint according to the wearer's voluntary walking period. In our past studies,(1)(2)(3) several models were developed and examined in the clinical tests by the amputees. Those models have had a new function being able to change their damping moment around the knee-joints by alteration of air-flow pathes according to a mean value of EMG. It was verified that those models could be adaptable to the amputee's voluntary walking period in rather slower range, while it was also verified that the amputees could not walk fast with wearing them. There was the similar study by W.R.Dyck(4) in which the damping moment around the hydraulic knee joint was regulated by alteration of two solenoid valves and interval of their turning-on, and EMG was also used for voluntary control. The several problems might be pointed out in these studies included ours:

1) A subtle control might be impossible and electric power dissipation might be large by means of solenoid valves. 2) A whole system might become heavy.3) A discrimination of walking period by a level detector of integrated value of EMG might be rather rough for precise control. In our further studies being discussed below, these problems were considered and basically solved.

This paper deals with the development of the A/K prosthesis model WLP-6 system being able to regulate its damping moment to enable for an amputee to walk with his voluntary walking period, moreover being able to generate a little driving moment to enable him to walk more rapidly with it. On the first section, the dynamical analysis of a motion of a shank during a swing phase will be discussed. The design and composition of the hardware of WLP-6 system will be discussed the following sections. The algorithms for EMG processing and the prediction of the next step's walking period by EMG will be successively discussed. The walking experiments of WLP-6 system by the amputees and their results will be finally discussed.

2 The dynamical analysis of a shank during a swing phase

In order to develop an A/K prosthesis being capable of regulating its moment around the knee-joint, it must be estimated how much the moment should be generated around the knee-joint. So that the dynamical analysis of a shank during a swing-phase was performed. A movement of a lower limb during a swing phase was apploximated to those of a two-rigid links shown in Figure 1. The motion equation obeying to this model is as follow.

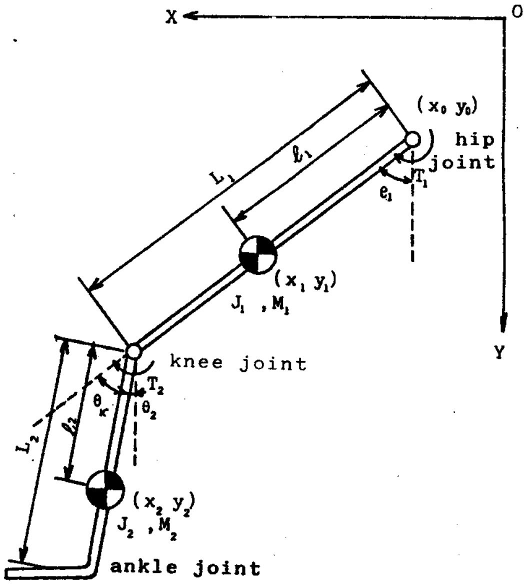


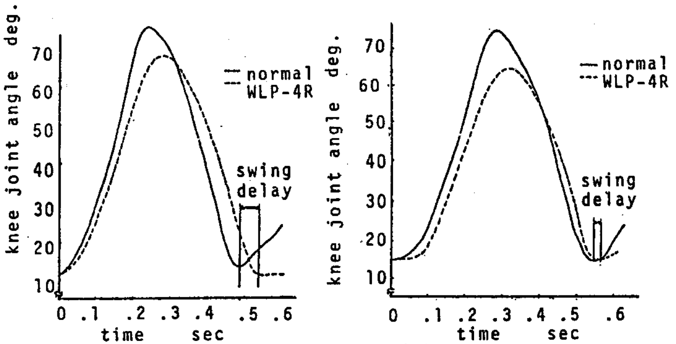
Fig.1 Two rigid link model for below limb during a swing phase.

$$(J_2+M_2 l_2^2)(\ddot{\theta}_1-\ddot{\theta}_K)+M_2 L_1 l_2 \ddot{\theta}_1 \cos\theta_K - M_2 L_1 l_2 \dot{\theta}_1^2 \sin\theta_K + M_2 l_2 \{\ddot{x}_0 \cos(\theta_1-\theta_K)-\ddot{y}_0 \sin(\theta_1-\theta_K)\}+M_2 g l_2 \sin(\theta_1-\theta_K) = T_2 \quad (1)$$

The damping (passive) moment around the knee-joint was estimated as equation (2) from the thermo-dynamical analysis of a pneumatic piston-cylinder of a knee-joint.

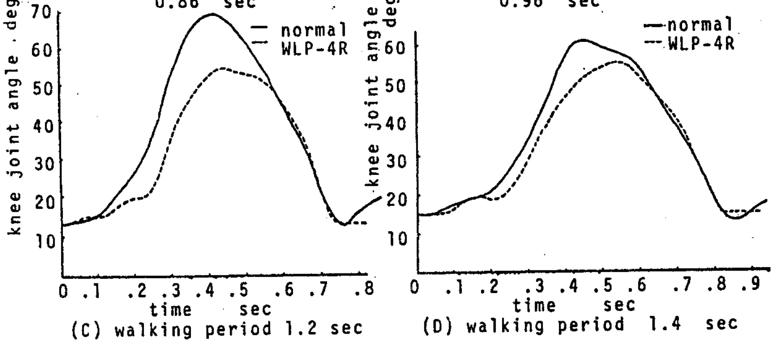
$$T_2 = -\mathrm{sgn}(\dot{\theta}_K)(R\dot{\theta}_K^2+T_F) \quad (2)$$

where TF is a friction-moment and R is a damping coefficient which is a variable for regulating the damping moment. All physical constants and the variable range of the value of R of the model WLP-4R developed in 1978 were used as those of the equation (1). The coordination of hip-joint (X_0, Y_0) and the hip-joint angle θ_1 of a normal during the level walking were measured by the two-camera optoelectronic digitizer (Selspot). On the first process, the data of (X_0, Y_0) and θ_1 were



(A) walking period 0.86 sec

(B) walking period 0.96 sec



(C) walking period 1.2 sec

(D) walking period 1.4 sec

Fig.2 The results of the dynamical analysis of a shank during a swing phase. All physical constants are of WLP-4R.

approximated to Fourier series function to proceed the first and the second differentiation with respect to time. These data were succeedingly substituted into the dynamical equation (1) combined with (2) to obtain the time-variation of θ_K by Runge-Kutta integration method. The results of this procedure are illustrated in Figure 2. The calculation was performed with regard to four walking periods as shown in Figure 2 ,in which it turned out that swing delay (the state being not in enough extention) happened in the respective fast walking-periods no matter how elaborately the coefficient R was adjusted. As the next step,θ_1 ,θ_K,(X_0,Y_0) and their differentiated data were all substituted into the equation (1) combined with (2) to obtain the time-variation of the knee-joint moment T_2 which means the moment for A/K prosthesis model WLP-4R to move like a normal, the results of which was illustrated in Figure 3. It can be shown in Figure 3 that the driving (active) moment should be generated at the beginning of an extension. From these results shown in Figure 2 and Figure 3, it was concluded that some amount of driving moment should be generated to prevent the swing delay, for walking fast.

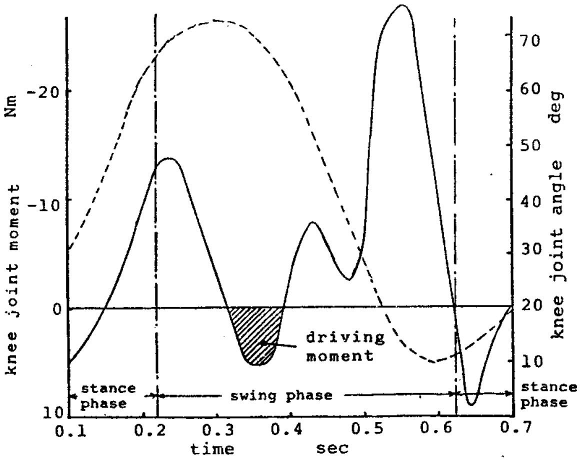


Fig.3 The knee joint moment for making a shank of A/K prosthesis swing as well as a normal.

knee joint angle

knee joint moment

3 The design and construction of A/K prosthesis WLP-6

From the results of the dynamical analysis mentioned above, the new type of A/K prosthesis WLP-6 being adjustable its damping moment and being able to generate a little amount of driving moment was designed and constructed.The structure and the appearance of WLP-6 are shown in Figure 4. WLP-6 has the following two important mechanisms.

1) The mechanism for control the damping moment::

A pneumatic closed loop is consisted with a piston-cylinder and a

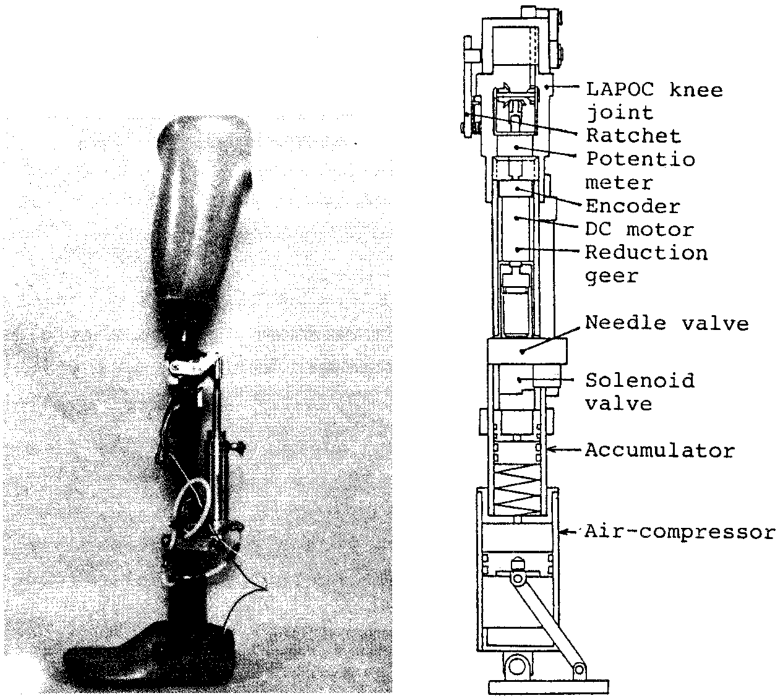


Fig.4 The inner structure and the appearance of WLP-6

needle-valve rotated by a DC-motor. This mechanism has the following advantage.

(a) The automatic subtle adjustment is capable with it.

(b) The DC-motor and the needle-valve can be enclosed into the pylon so that a compact design is achieved.

2) The mechanism for generating driving moment::

This mechanism is consisted with a solenoid-valve, an air-accumulator and a compressor which is actuated by rotation of the ankle-joint during a stance-phase. The compressed air accumulated in the accumulator during a stance-phase is injected into the piston-cylinder of the knee-joint by opening the solenoid-valve at an extension during the following swing-phase, so that the shank will be actively swung. One of the great advantages of this mechanism is to be able to generate driving moment without any power sources except a battery for the solenoid valve.

The almost all material of the structural parts is carbon-fibre and duralumin. The part of the knee-joint is a modular part of LAPOC system prosthesis. The whole weight of the below-knee is about 2.3 kg. The value of the driving moment which WLP-6 can generate was turned out to be about 1.0 Nm from the result of the step-response examination.

4 The prediction of walking period by EMG

4.1 The introduction of EMG

It belongs to intention of a wearer of an A/K prosthesis how fast he is going to walk in the next walking step, so that his intention must be estimated in advance to adjust WLP-6 according to the next step's walking period. EMG will be considered as a most available myo-signal which transmits his intention. However there will be the following troublesome problems on dealing with EMG, which should be effectively solved.

(1) The potential of EMG depends on person's fatigue and perspiration.

(2) EMG is a minute electric signal so that the electromagetic or current noise will be liable to contaminate with it.

(3) Its statistical properties depends on figure of a surface electrode.

In the following paragraph, how the above three problems was dealt will be discussed.

4.2 A surface electrode

The EMG potential picked up by a surface electrode is those of spacio-temporal superposition of some MUAP (Motor Unit Action Potential) which is emitted from each muscle fibre along which electrical impulse trains fired on MU (Motor Unit) are transmitted. The number of MU is distributed equally in the muscle.(5) Therefore the number of MU influenced to a surface-electrode might be rather small. Moreover, MUAP is attenuated on a process of transmission among muscle tissue and on a skin. Hence EMG potential picked up by a surface-electrode might be a result of a superposition of a few number of MUAP, which will causes statistical unstability of EMG potential. The other important factor should be in consideration is a distance between two pieces of a differential electrode. There has been some basic studies(6) in which the wider distance between two pieces of a differential electrode causes the narrower range of the spectrum of EMG potential, which will also causes unstability of it. Taking above matters into consideration, the following speculation will be proposed: In order to obtain statistically stable EMG potential, the figure of a differential surface-electrode must be long rectangle having enough area, and the distance between two pieces must be in 5 mm so as to expand the range of spectrum by 500 Hz assumed the transmission rate of MUAP is about 5~6 m/s. The surface-electrode and the pre-amplifier composed is shown in Figure 5. The electrode was made of stainless-foil attached on the rubber of 1 mm thickness. The whole thickness of the electrode is in 3 mm so that it can be inserted into an amputee's socket without any amputee's uncomfortable feeling.

4.3 Location and timing for picking up EMG potential

EMG potential is picked up on a residual leg during a stance phase. It is desirable for a location of an electrode to be picked up EMG having information of walking period. On our basic analysis of EMG picked up from various places of a thigh, it turned out that EMG picked up on M.iliacus had the most amount of information of walking period.(3) And EMG data during more than 60 msec from a heel-contact was the most suitable and stable for obtaining information. The sample of EMG potential picked up on M.iliacus is shown in Figure 6.

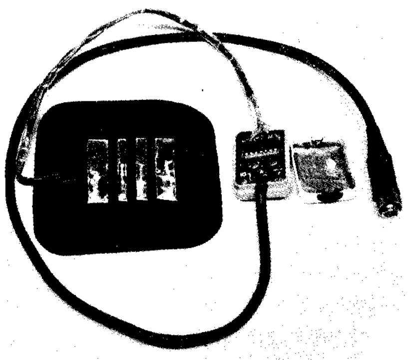


Fig.5 The surface electrode and the pre-amplifier.

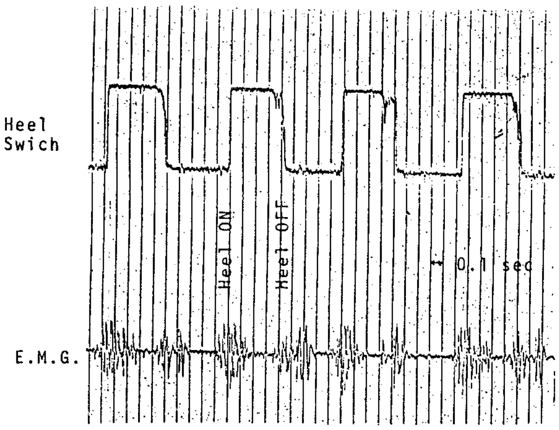


Fig.6 The sample of EMG potential of M.iliacus on level walking

4.4 The software treatment of EMG having high-pass filtering effect

There are three sorts of low-frequency noise contaminated into EMG potential on a process of its picking up and amplifying.

(1) The extra-low-frequency noise caused by thermo-drift of an

electronic circuit.

(2) The artifact by bending of wire which transmit EMG potential to an amplifier.

(3) The electromagnetic noise from AC electric power sources or fluorescent lamp, etc.

These low-frequency noises should be eliminated by an electronic circuit and also a software treatment. N.Hogan proposed the value of a standard deviation (SD) as an EMG signal for measuring muscle force, whose advantage was to be able to eliminate DC noise.(6) In our further study, it was theoretically clarified that the operation for SD has an approximate effect of first-order high-pass filtering in the realm of frequency. Furthermore, the original software algorithm for varying the cut-off frequency in the calculation of SD was proposed. The equation for calculating EMG data having high-pass filtering effect is as follow.

$$E = \sum_{j=1}^{m} \sqrt{\sum_{i=1}^{n} e_{ij}^{2} - \frac{1}{n} \left(\sum_{i=1}^{n} e_{ij} \right)^{2}} \quad (3)$$

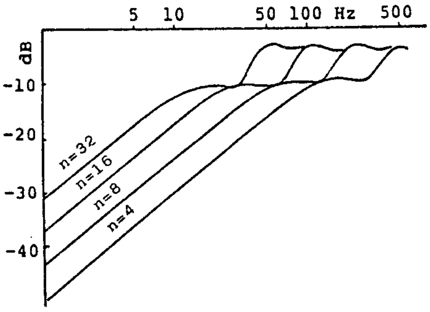


Fig.7 The bode diagram of the high-pass filtering effect on the software treatment of EMG. "n" is the number of sampling data in one block.

The whole sampling data (eij, i=1,2,...,n j=1,2,...,m) are divided into "m" blocks each of which has "n" sampling data. One EMG datum "E" is the summation of "m" standard deviations of "n" sampling data. The cut-off frequency of this procedure are determined by the number of "n" and a sampling rate. The theoretical Bode-diagram of this procedure is illustrated in Figure 7. The optimal number of "n" for eliminating low-frequency noise effectively was determined by the following experiment. The EMG data were recorded on the magnetic tape when the normal subjects walked with several constant walking periods. Then the value of "E" of equation (3) and their mean value on several walking periods were calculated.

Finally their normalyzed standard deviation (NSD); the SD divided by the mean value, was calculated, i.e., the value of NSD shows how clearly walking period are discriminated in the value of EMG data. The result of this examination are illustrated in Figure 8. As shown in Figure 8, it turned out the optimal number of "n" is eight (at sampling rate; 2000 Hz).

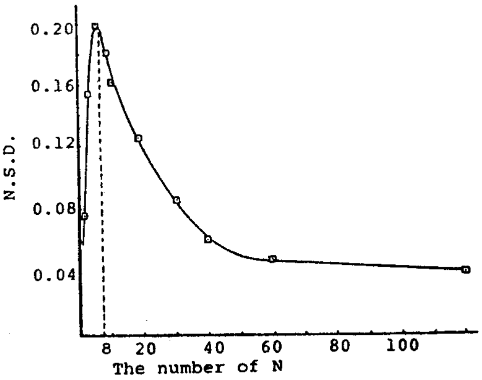


Fig.8 The normalized standard deviation (NSD) as a index value showing how clearly walking period was discriminated from EMG data.

4.5 The algorithm for prediction of walking period

As discussed in the paragraph 4.1, the EMG potential of EMG potential picked up by a surface-electrode depends on a person's fatigue and perspiration. Therefore the relative coefficient between EMG datum and walking period must be always regulated. Furthermore, the next step's walking period must be predicted by EMG data to adjust the damping coefficient of WLP-6. These problems were solved by the following algorithm.

$$\hat{y}_t = y_{t-1} + K(E_t - E_{t-1}) \qquad (4)$$

where, yt-1 is a reciprocal value of a measured walking period of t-1th walking step and Et and Et-1 are the EMG data (the result of equation (3)) of t-th and t-1th walking step respectively. The difference between Et and Et-1 is multiplied by the weight-parameter K and added to yt-1 to obtain a reciprocal value of a predicted walking period of the next step; ŷt. The weight-parameter K is always regulated by the least square method.

$$K = \frac{\sum_{\nu=t-m-1}^{t-1} (E_\nu - E_{\nu-1})(y_\nu - y_{\nu-1})}{\sum_{\nu=t-m-1}^{t-1} (E_\nu - E_{\nu-1})^2} \qquad (5)$$

where, the past "m" EMG data and data of walking-period were used. The optimal number of "m" to minimize the error between predicted and measured walking period was evaluated to 15 by the walking experiments.

5 The control of WLP-6

From the dynamical analysis during a swing phase based on the physical constants of WLP-6, it turned out the following control method according to walking period was the most effective. The damping moment should be increased for fast walking period during knee-flexion, while it should be reduced during knee-extension. On more fast walking period, driving moment should be generated during knee extension. This method has been implicitely suggested by the similar dynamical analysis during a swing phase of D.Mena.(7) The control sequence for WLP-6 is summarized in Table 1.

Table 1 The control sequence for WLP-6

phase		time	control sequence
stance phase		0.1	A/D conversion of EMG composition of EMG data,E
		0.2	prediction of the next step's walking period
		0.2	reguration of needle valve compression of air
swing phase	flex.		generation of the damping moment according to the predicterd walking period
	ext.		solenoid valve-ON → driving moment generates

6 The WLP-6 control unit

The WLP-6 control unit based on the micro-computer (z-8;CPU) was composed, whose block diagram is shown in Figure 9. This control unit operates the following subsequent procedures in one walking step.

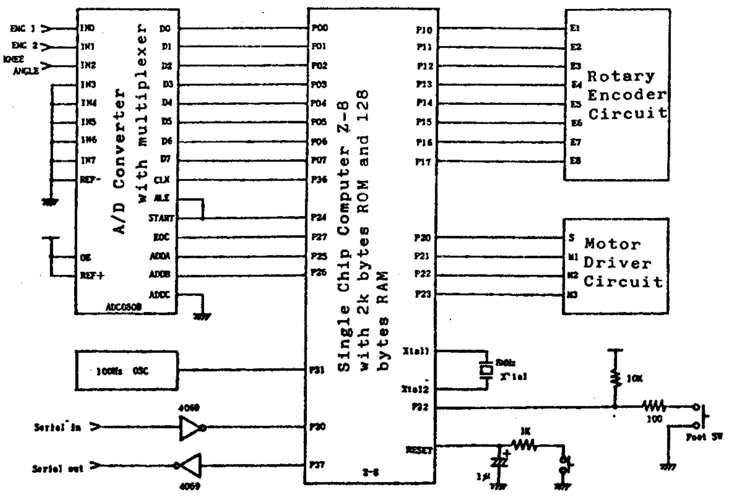


Fig.9 The block diagram of the WLP6 control unit

(1) It converts EMG potential to digital data from the beginning of a heel-contact and predicts the next step's walking period by them.
(2) It adjusts the rotational degree of the needle-valve in accordance with the next step's walking period by rotating the DC motor.
(3) It opens the solenoid-valve at an extension period to generate driving moment.

This control unit was composed so as to be compact and low-power dissipation as far as possible by making use of a single-chip computer;z-8(ZILOG) and mos-ICs.

7 The walking experiment for WLP-6

The walking experiment wearing WLP-6 was performed with the help of two amputees (Mr.H; 20 years old, Mr.S; 57 years old). The appearance of the walking experiment of subject H is shown in Figure 10. The WLP-6 control unit and the battery were attached on their back.

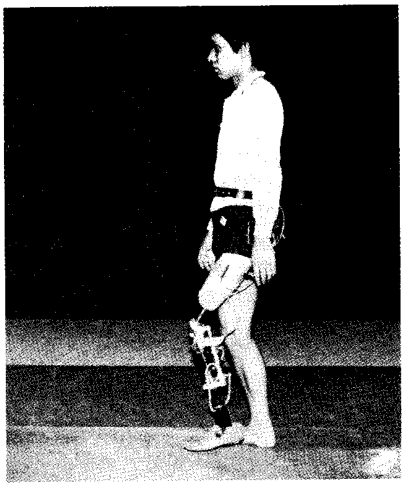


Fig.10 The walking experiment for WLP-6 by amputees.

On the first time, the subjects walked with several constant walking periods adjusting the rotational degree of the needle-valve and designated the most suitable rotational degree of the needle-valve on each walking period after enough training of walking.The results of this auxiliary experiments are illustrated in Figure 11. Figure 11 showed that the subjects could walk in the range of walking period;1.1 ~ 1.6 sec, although there was the difference between the subjects. This walking period coincides with those of a normal. As the second step, the relation between walking period and the rotational degree of the needle-valve obtained in the auxiliary experiment was inputted into the WLP-6 control unit, then the walking

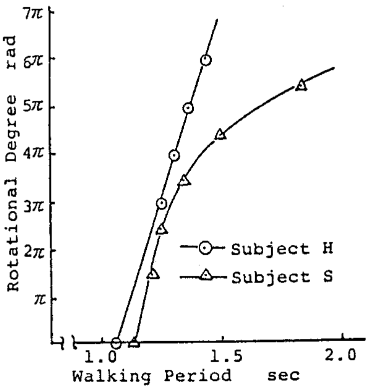


Fig.11 The adequate relation between rotational degree of the needle valve and walking period

experiment with the subject's voluntary walking period was performed. The results of the walking period of the next walking step predicted by the control unit were illustrated in Figure 12, the results of which showed that algorithm had predicted the next step's walking period within the negligible prediction error. The control unit could adjust the needle valve within 0.4 sec from heel-contact, therefore the whole adjustment could completely be terminated in a stance phase (at least 0.6sec).

The subjects didn't feel any burden by the weight of WLP-6 (2.3 kg) and felt the smoothness of knee-extension, which was considered as the effect of the driving moment generated at extension.

8 The conclusion

The walking experiment by the amputees showed WLP-6 has the same function as a normal concerning to the function being able to walk with voluntary walking period. The further study for multi-functional A/K prosthesis has now been going ahead.

Finally, let us show our acknowledgement to Mr.Ehara and the other all staffs in Kanagawa General Rehabilitation Center for their help on the walking experiment and also let us show our deepest thankfulness to the subjects; Mr.Harada and Mr.Sugano.

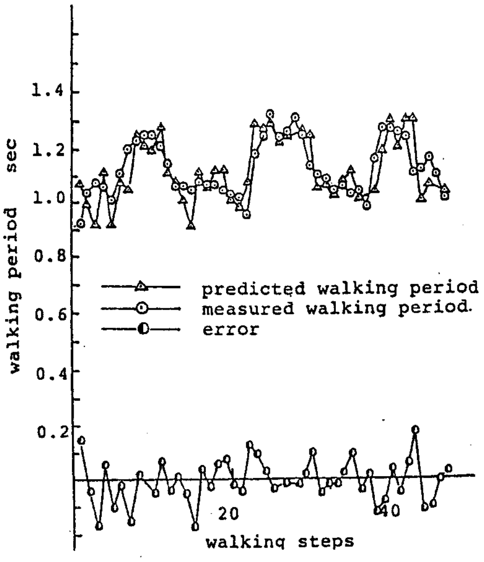


Fig.12 The predicted walking period and the measured walking period.

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