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ERGONOMICS, 1971, VOL. 14, NO. 3, 333–361

Foot Operation of Controls

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The literature pertaining to foot operation of controls is reviewed and a new experiment reported.

Published experimental results clarify only some isolated aspects of leg and foot motions. Even the relatively often investigated speed of operating pedals and forces that can be applied to them, were studied under such different experimental conditions that no general statements are possible concerning what pedal can be operated most quickly or forcibly. Opinions about the advantages and disadvantages of hand versus foot operation seem not generally based on experimental findings.

In an experiment, 20 seated young adult male subjects moved their right foot as rapidly as possible over distances of 15 cm to circular targets. The direction of these discrete movements had no appreciable effect on the accuracy of motion. Forward motions of the vertical or almost vertical lower leg were slightly faster than backward or lateral motions of the elevated lower leg. All motions could be performed in about 0·1 seconds.

1. Introduction

'Examples of human controlled mechanisms in which the feet assume portions of the control function abound: automobiles, airplanes, and musical instruments, for example. But almost never is primary control of a process given over entirely to the feet, though there may be a clearly obvious adantage in having the hands free for other tasks. The reason for this probably lies in the relatively gross nature of typical neuromuscular behavior of the feet, with the attendant difficulty of training them for a delicate task. But if the feet and legs are already highly trained for the task, in fact so highly trained that the necessary delicate responses have become reflexes, they should be able not only to do the job adequately, but to do it with practically no training and very little demand on the higher neural centers. Allowing such a function to assume some primary control duty, then, should free the hands and mind for other primary duties and thereby make the overall system more flexible, more capable, and/or more economical.'

Since Keller and O'Hagan (1963) wrote those sentences the literature shows no evidence of more studies than before being devoted to the question of 'hand versus foot operation of controls'. Despite the practical importance of this problem, surprisingly little research has been published indicating the possibilities and limitations of using the feet for inputs to man–machine systems.

This report contains a review of the literature pertaining to foot operation of controls, and a description of experiments on the speed and accuracy of discrete foot motions.

2. Literature Review

2.1. *Speed of Activation of Foot Controls*

Barnes *et al.* (1942) were the first of several experimenters studying the operation of a particular group of pedals as sketched in Figure 1. All the pedals had in common that they were rotated with the foot about a pivot near the pedal surface. This pivot was located at the rear end of the pedal, or at the front, or somewhere in-between.

In their study, ' 12 male and 3 female ' sitting subjects depressed each pedal with the right foot as often as possible during a period of three minutes. Unfortunately, not all experimental data are reported: questions remain, e.g., with respect to the initial position, the resistance of the pedals and the amount of travel (Table 1). Barnes *et al.* concluded that hinging the pedal at the rear

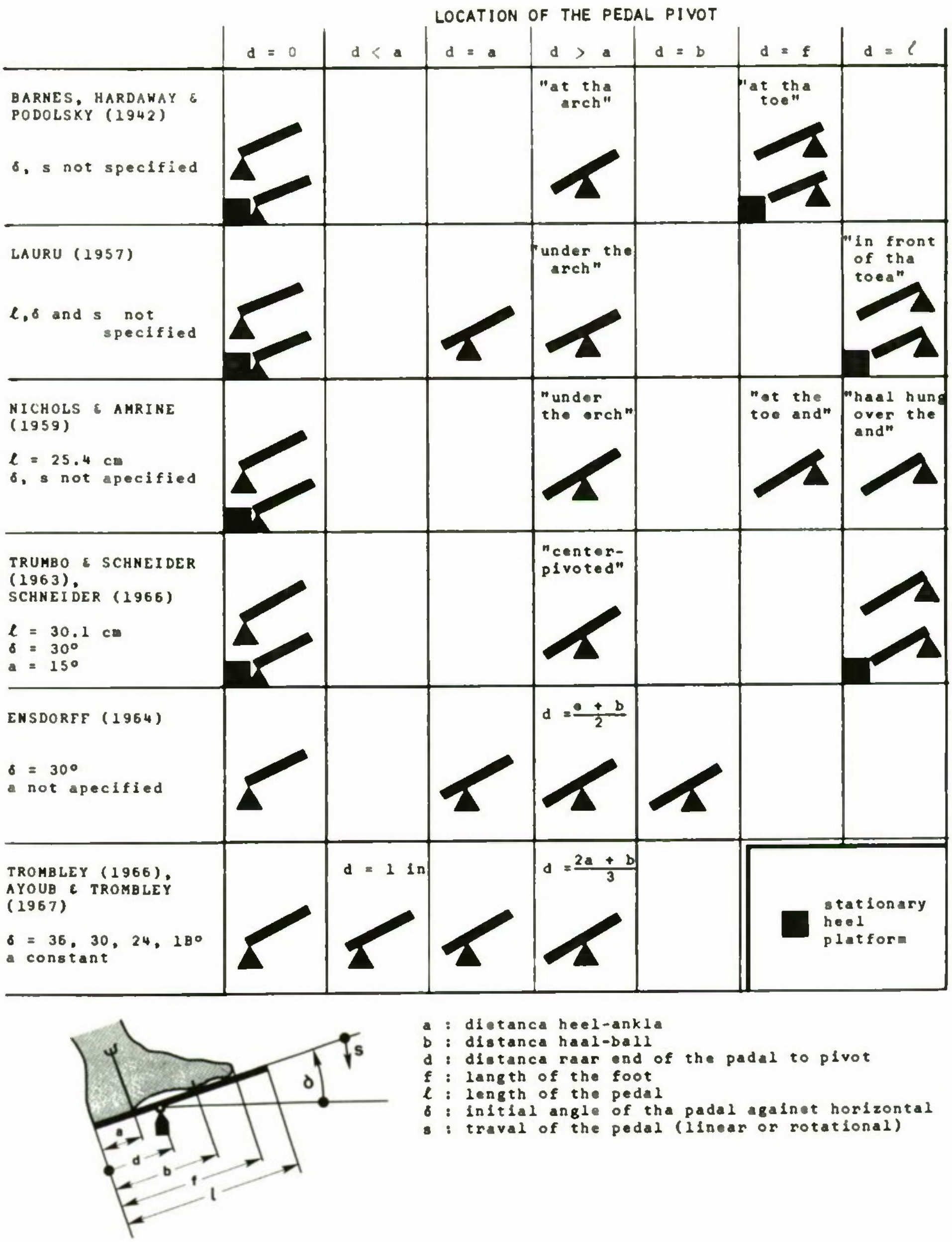

Figure 1. Location of the pivot in previous pedal experiments.

Table 1. List of experimental parameters in the pedal studies of

Barnes, Hardaway and Podolsky (1942)	BHP
Lauru (1957)	L
Nichols and Amrine (1959)	NA
Trumbo and Schneider (1963), Schneider (1966)	TS
Ensdorff (1964)	E
Trombley (1966), Ayoub and Trombley (1967)	T

	BHP	L	NA	TS	E	T
Subjects						
Sample population	?	?	X	X	?	X
Males	X	?	X	X	?	X
Females	X	?	–	–	?	–
Thigh angle	?	?	?	?	X	X
Knee angle	?	?	?	?	X	X
Tibia-pedal angle	?	?	?	?	X	X
Sitting	X	X	–	X	X	X
Standing	–	–	X	–	–	–
Pedal						
Length	X	?	X	X	X	–
Breadth	X	?	X	X	X	–
Pivot location	X	X	X	X	X	X
Initial position	?	?	?	X	X	X
Initial balance	?	X	X	?	?	X
Force, etc., necessary	?	X	?	X	?	X
Action required						
Travel to mark	–	?	?	–	X	–
Travel to stop	X	?	?	X	–	X
Travel given angle	?	?	?	X	?	X
Travel given distance	?	?	?	–	?	X
Discrete motions	–	?	?	X	X	X
Repetitive motions	X	?	?	–	–	–
Rating criteria						
Force, work, etc.	–	X	?	–	–	–
Number of operations	X	?	?	–	–	–
Reaction time	X	?	?	X	X	X
Travel time	X	X	?	X	X	X
Accuracy	–	?	?	–	X	–
Physiologic strain	–	–	X	–	–	–

X = specified by the author. ? = not specified. – = not applicable.

or at the front allowed subjects to perform the maximal number of (attempted and completed) strokes per minute. Using stationary platforms for the heel of the foot, or hinging the pedal ' at the arch ' of the foot reduced the stroke frequency.

Lauru (1957) also used similar pedals, but had in addition one with the pivot ' in the axis of the tibia ' under the heel. No description of the pedal dimensions, excursions, resistances, etc., is given except that the pedals ' activated a cutting press '. Lauru measured the forces exerted on the pedals and the time consumed in their operation. He found that the pedal hinged under the heel could be activated fastest and required least force for operation by a sitting subject. The pedals hinged ' under the foot arch ' and at the rear end were the next best while the front-hinged pedals needed most force and time for activation.

Nichols and Amrine (1959) claim to have used the same pedals as Barnes *et al.* Unfortunately, they also do not report the initial position or the amount of travel of the pedals. The pedals offered three levels of resistance to the operation, since weights of 5 lb, 10 lb, and 15 lb were attached to them through cables and pulleys. The authors do not specify what amount of force or work was required to move the pedals. Five male college students (' between the ages of 17 and 25 years ') operated the pedals while standing. Manner and frequency of operation are not reported. The authors state that the smallest increases of the subjects' heart rates occurred when they operated pedals hinged at the rear or at the front.

Trumbo and Schneider (1963) also used Barnes' pedal types. In the initial position, the pedals were inclined at 30 degrees. From this position the pedals had to be pressed down 15 degrees against a spring. This action required a work of about 2·6 in. lb. Ten male college students, while sitting, operated the pedal as fast as possible upon a light signal. Discrete activations were required rather than continuous operation as in Barnes' and Lauru's studies. Trumbo and Schneider found that the response times (reaction plus motion time elapsed until pedal was 15 degrees depressed) were smallest with the pedal hinged at the rear, and largest with the pedals pivoted at the front.

Ensdorff (1964) investigated pedals hinged at the heel, under the ankle, under the arch, and under the ball of the foot. His eight subjects (20 to 35 years old) sat on a chair, their thighs horizontal, their shins at angles of 90, 100, 110, 120 degrees with the pedal surface in the initial position, which was 30 degrees over horizontal. Upon a light stimulus, the subjects depressed the pedal as fast as possible to move a pointer 7·5 cm to a fixed mark. The report does not clarify the actual travel of the pedal or the force required; it is obvious, however, that four different resistance levels were employed. Ensdorff measured reaction time (from the onset of stimulus to beginning of pedal motion), travel time of the pedal, and deviation of the pointer from the goal mark. He found that the reaction time was longest with the pedal hinged at the rear. Travel time, however, was shortest with the same rear-hinged pedal and increased with more anterior pivots. The accuracy of pointer (pedal) motion was best with the pivot under ankle or arch of the foot.

Trombley (1966) and Ayoub and Trombley (1967) used pedals hinged at the rear of the foot, under the arch and in two intermediate locations. Fifteen male subjects, seated in a dentist chair, had to depress the pedals in discrete movements as fast as possible to a fixed stop. The stop was adjusted to require travels of 12 degrees or, respectively, of ¾ in. at the ball of the foot. In the starting position, the subject's thigh was horizontal, the knee at 114 degrees, the angles between tibia and pedal were 78, 84, 90, or 96 degrees. The system was balanced so that the starting position could be maintained without muscular effort. Work of 8·4–34·2 in. lb. was necessary to move the pedals.

Trombley's results can be summarized as follows.

Reaction time was independent of the location of the pivot. Reaction time increased with increasing resistance of the pedal. Reaction time was shortest with an initial angle of 78 degrees between foot and pedal, and increased linearily with increasing initial angles. These findings held true both for constant travel distance and constant travel angle.

Travel time through a constant 12 degrees was largest with the rear-hinged pedal and decreased linearily with more forward pivot locations. However, the time consumed to travel a constant $\frac{3}{4}$ in. at the ball of the foot was shortest with the rear-hinged pedal and increased when the pivot was located more forward. Travel time was shortest with the smallest pedal resistance and increased with larger loads. Travel time was somewhat irregularly related with the pedal–tibia angle, but seemed to be shortest with the smaller angles. Travel through the constant angle of 12 degrees was faster than through the constant distance of $\frac{3}{4}$ in. at the ball.

Konz *et al.* (1968) reported on experiments with an automobile pedal combining brake and accelerator controls. This pedal was supported by two shafts perpendicular to the pedal surface. Pressing down the front part (' accelerating ') moved the anterior shaft down, the pedal then pivoting about the hinge attaching it to the posterior shaft; pressing down the rear end, i.e., the posterior shaft (' braking ') caused the pedal to pivot about the hinge attaching it to the anterior shaft. Konz and co-workers found brake actuation starting from the depressed accelerator considerably faster with this dual pedal than with the conventional two-pedal arrangement. This laboratory finding was confirmed in actual automobile driving tests.

Konz and his colleagues then modified the combination pedal to find out whether the pivot locations affected activation time. They moved the brake and accelerator shaft of the pedal independently fore and aft. In this experiment, the interlocking device between the shafts was removed so both shafts could be pressed down simultaneously. Three female and 11 male subjects with at least two years of driving experience, average age 23 years, took part in the experiments. A ' chair with normally cushioned seat and back ' was so adjusted that the distance between the rear end of the pedal and the Seat Reference Point corresponded to 50% of each subject's height. The pedal was inclined 45 degrees, the angle between tibia and pedal between 78 and 96 degrees. Seat height and force necessary to move the pedal are not reported. The subject held the front part of the pedal down, waiting for a red light to come on. Upon this signal, he quickly depressed the rear part of the pedal. The time from onset of the light to depressing the rear end of the pedal by at least $\frac{1}{16}$ in. was measured.

No significant interactions between pivot locations and brake activation times were found, although the distances from the rear edge of the pedal to the brake shaft were varied from 0·5–2·5 in. and the distances from the rear to the accelerator shaft were adjusted from 5–9 in.*

The great majority of experiments was conducted with pedals similar to those used by Barnes *et al.* (1942). Yet, there are significant differences among these studies with respect to basic experimental conditions. Some important experimental parameters are not reported, and the criteria applied are not the same throughout (see Figure 1 and Table 1). Thus, not even for ' pedals pivoted near the foot ', is a general statement possible as to what pedal allows the fastest discrete activation or the highest frequency in repetitive operation under certain requirements of position, resistance, displacement, accuracy, etc. For the many other possible and actually used pedal designs

* Further experiments were recently reported (Konz *et al.* 1969).

and modes of operation, almost no information is available from the open literature.

2.2. *Forces Applicable to Pedals*

Statie forees that sitting operators ean apply to pedals have been measured by a number of researehers. The forees were exerted with one leg to fixed pedals, without gross relative movement of the pedal, foot, or leg. Results of the experiments are eompiled in Tables 2 through 5. Figure 2 identifies body posture and body support during pedal operation.

Forees applieable to aireraft pedals were of interest 40 years ago. Hertel (1930) used a Junkers aireraft moekup to measure the leg strength of 11 engineers and pilots. As shown in Table 2, the mean forees fell from 220 kp*

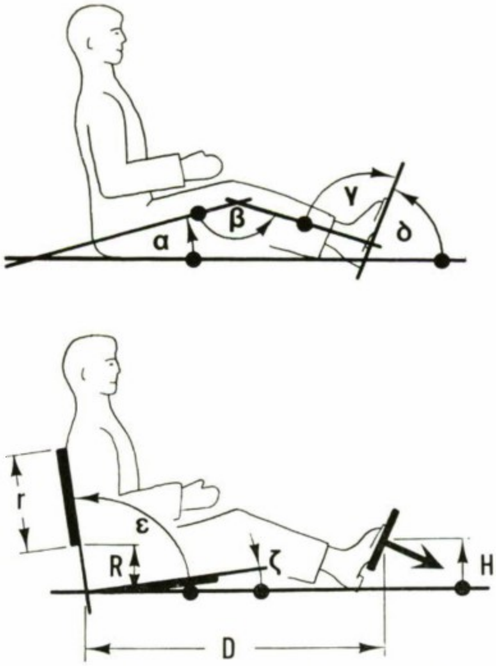

Figure 2. Identification of body posture and body support during pedal operation.

Table 2. Maximal static leg thrust exerted by seated males on aircraft-type pedals

Test Conditions (See Figure 2)						Force			
Type of pedal	Type of seat	β degrees	γ degrees	D cm	H cm	Mean kp	S.D. kp	Remarks	Subjects (author)
Junkers Ju 35 cockpit		—	—	—	—	220	20	Subjects fresh	11 pilots and engineers (Hertel 1930)
		—	—	—	—	67	7	Subjects fatigued	
Cockpit mock-up		—	—	89	−15	190	—	Horizontal force	2 pilots (Gough and Beard 1936)
		—	—	84	−30	159	—		
B-24 aircraft cockpit		111 ± 5	120 ± 5	—	—	257	appx. 45	—	515 student pilots (Elbel 1949)

* Kilopond kp, formerly kilogram-force kgf.

to about 70 kp when the subjects were fatigued after sustained force exertion. Gough and Beard (1936) showed that the mean force decreased from 190–159 kp when the pedal was lowered from 15–30 cm below seat level. Elbel (1949) measured average forces of almost 260 kp at B-24 aircraft pedals, when the knee angle of his subjects was about 111 degrees and the angle between the lower leg and the pedal about 120 degrees. However, Crawford (1953) reported

Table 3. Maximal static leg thrust exerted by seated subjects on pivoted pedals

Test conditions (See Figure 2)							Force		Subjects (authors)
Type of pedal	Type of seat	α degrees	β degrees	γ degrees	D cm	H cm	Mean kp	Direction	
Pivoted near the instep approximately in line with the axis of the tibia; large enough to accommodate the entire foot	R = 14 cm r = 12 cm ϵ, ξ = 0*	Between −10 and +24	130–150	90	—	Between +10 and −10	Appx. 200	5° to 15° below horizontal	1 man
							appx. 154		2 women (Müller, 1936)
	back rest supports pelvis and back. ϵ, ξ = 0†	−6	94	90	—	—	33	Approximately in the line from the hip joint to the centre of the pedal	6 'powerfully built men ' (Hugh-Jones 1947)
		−15	149	90	—	—	103		
		−10	162	90	—	—	175		
		−10	165	90	—	—	157		
		−9	167	90	—	—	114		
		8	93	90	—	—	40		
		10	136	90	—	—	123		
		5	164	90	—	—	254		
		19	67	90	—	—	41		
		16	129	90	—	—	145		
		15	160	90	—	—	384		
		15	160	90	—	—	(314)†		
		15	160	90	—	—	(313)‡		
		15	169	90	—	—	241		
		36	88	90	—	—	61		
		33	106	90	—	—	84		
		34	125	90	—	—	201		
		48	72	90	—	—	60		
		49	81	90	—	—	59		
Pivoted under the ball of the foot; pushed with the ball. Pedal 12·7 cm wide, 6·4 cm long	R = 20–29 cm r = 12·7 cm ϵ, ξ = 0*	15	160	—	—	13	174	Horizontal	20 men (Rees and Graham, 1952)
		0	160	—	—	−10	145		
Pivoted near the shin§ pushed with ball of foot	not described	—	—	90	84 ± 5	6 ± 15	329 (median)	Direction of force parallel to the lower leg§	166 tank personnel (Martin and Johnson, 1952)

* Probably 0°, but not explicitly stated in the original publication.

† 32 drivers of the Royal Armoured Corps.

‡ 16 schoolboys, aged 14 to 18.

§ Force application pushed the pedal assembly into the direction of thrust.

that the pedal assembly of a taxying aircraft was broken by the pilot, who obviously had applied more than the mere 220 kp until then officially specified as the maximal design load. Crawford cites subsequent tests with 10 pilots showing forces up to 445 kp applied to aircraft pedals.

Forces exertable at pivoted pedals are compiled in Table 3. Müller (1936) was the first and apparently the only researcher to publish such strength data of (two) women in addition to data of (one) man. Müller found considerable interindividual strength differences between his subjects. The two females were much weaker than his male subject. Regardless of the absolute scores, each subject could exert his individual maximal force when the pedal was in front of the hip joint, at about seat height, and so far away that the knee had to be straightened to about 130 to 150 degrees to reach the pedal. The force was diminished if the seat had no backrest, or if the pedal was moved forward, backward, or laterally, or lowered from its position in front of the hip joint. Müller's colleagues, Dupuis *et al.* (1955), Lehmann (1958), Coermann and Kroemer (1968) gave some additional details of Müller's experimental results, not explicitly stated in his original publication. Müller found that the maximal force could be transmitted to the pedal with the instep of the foot over the pedal axis, and that there are no gross strength differences between the right and left leg.

Hugh-Jones (1947) also used a pedal pivoted near the instep, approximately in line with the axis of the tibia. He found that his subjects (six ' powerfully built men ') could exert largest forces on the pedal when the knee angle was at about 160 to 170 degrees, i.e. at larger angles than Müller had found to allow the strongest thrust. As in Müller's experiments, the largest force could be exerted when the pedal was located in front of the hip joint. In this position, Hugh-Jones observed no gross differences in the mean forces of 32 drivers of the Royal Armoured Corps and of 16 London schoolboys, aged 14–18 years whom he used as subjects in addition to his original six. Hugh-Jones' data show that seemingly small changes in knee or hip angle may bring about rather large changes in the forces applicable to the pedal.

Rees and Graham (1952) had their pedal pivoted under the ball at the foot; from the drawing in their report, it seems as if the axis of rotation was about 2·5 cm below the surface of the pedal. Twenty men pushed at the pedal with the ball of the foot. Rees and Graham stated that the position of the backrest of the seat is an important factor with regard to the force that can be exerted. The way reaction force is provided to the subject determines the force he can actively exert; the amount of force he can exert actively is limited to the amount of reaction force available to him. Rees and Graham showed again how the force applicable to the pedal is diminished when the pedal is lowered from the height of the hip joint to a location well below the seat height.

Martin and Johnson (1952) also used a pivoted pedal. Its axis of rotation, however, was not near the pedal surface but close to the subject's shin. This meant that the pedal swung into the line of thrust but also that the axis ' interfered with the subject's leg when small horizontal distances (between the pedal and the junction of seat pan and backrest) were used. As a consequence, horizontal distances less than 29 in. could not be tested '. The subjects, 166 members of a tank battalion, pushed with the ball of the foot. Martin and Johnson found that their subjects could exert largest forces when

Table 4. Maximal static leg thrust exerted by seated males on a fixed pedal

Test conditions (See Figure 2)					Force			
Type of pedal	Type of seat	γ degrees	D % of total leg reach	H cm	Mean kp	S.D. kp	Direction	Subjects (author)
Fixed pedal, pushed with ball of foot	R = 18 cm	90	95	30	139	32	Approximately	60 men
	r = 50 cm	90	85	30	105	30	in line from	(Rohmert
	$\epsilon = 20°$						hip joint to	1966)
	$\xi = 3°$	90	95	10	138	30	the ankle	
	(Akerblom)	90	85	10	123	30		
		90	95	− 5	143	31		
		90	85	− 5	129	30		
		90	95	−20	135	29		
		90	85	−20	115	32		
		90	95	−35	107	24		
		90	85	−35	107	30		

the pedal was at approximately the height of the hip joint, and at the rather short distance of only 80–90 cm in front of the junction of seat pan and backrest. Thus, with this pedal arrangement, highest forces could be applied with legs flexed.

Rohmert (1966) measured the forces that 60 men* could exert on a fixed pedal with the ball of the foot (see Table 4). The results show once more the decrease in exertable force when the pedal is arranged so close to the subject that the knee must be bent severely as compared to the force exertable with the leg about straight, and horizontal. There are some discrepancies in the magnitude of force between the data reported by Rohmert and the forces measured on pivoted pedals (Table 3): it is not clear whether the differences stem mainly from the use of different pedals, or of different subject populations, or from other experimental parameters.

Le Gros Clark and Weddell (1944) measured the force applied to pedals at the instant when their subjects moved their eye balls (' throw-off ' point). Their data are not directly comparable to any other but indicate that force exertion is facilitated by large knee angles.

Caldwell (1960) assessed the effects of the location of the pedal on the force that could be pulled horizontally on a handgrip. In this study, the pedal (footrest) was used to provide the sitting subject with the reaction force necessary for his hand pull. Caldwell states that ' the strength of the hand pull is greatest when the legs are in the position at which they can exert the greatest force against the foot-rest ', i.e., when the thigh is slightly elevated and the knee angle large, or, in other words, when the footrest is at about seat level.

Tables 2, 3, and 4, give the forces exerted in static thrust of the total leg, accomplished mainly by attempted changes in the knee and hip angles; Table 5, however, presents the force data of experiments in which the subjects exerted static force in attempted rotation of the foot about the ankle joint. (The data are based on Hertzberg's experiments described in 1960.) Predictably, these rotational forces are much lower than the forces exertable in total leg

* Rohmert and Jenik published in 1971 corresponding data for women.

Table 5. Maximal static foot forces exerted by seated males on an aircraft brake pedal by attempted rotation of the foot about the ankle

Test conditions (See Figure 2)					Force*			
Type of pedal	Type of seat	δ degrees	D cm	H cm	Mean kp	S.D. kp	Direction (degrees below horizontal)	Subjects (author)
F-80 aircraft pedal; axis of rotation under the heel	Hard surfaced plywood mockup of a standard aircraft seat	85	93 ± 3	−9	45	19	5	100 USAF pilots (Hertzberg, Anthropology Branch, Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, unpublished data)
		80	93 ± 3	−9	50	26	10	
		75	93 ± 3	−9	56	28	15	
		70	93 ± 3	−9	60	30	20	
		65	93 ± 3	−9	62	31	25	
		60	93 ± 3	−9	64	30	30	
		55	93 ± 3	−9	58	27	35	
		50	93 ± 3	−9	52	25	40	
		45	93 ± 3	−9	49	23	45	
		40	93 ± 3	−9	41	19	50	
		35	93 ± 3	−9	35	17	55	

* Exerted perpendicular to the pedal with the ball of the foot in attempted plantar flexion of the foot about the ankle. Force convertible into torque around pedal axis by multiplication with lever arm 15·6 cm.

thrust and depend on the pedal angle, i.e., on the angle between the lower leg and foot.

It is quite difficult to interpret and compare the published data on forces applicable to pedals.

First, the experimental parameters are not always completely described. What, for example, were the design and the arrangement of seat and pedal in the aircraft experiments listed in Table 5? How can the hip and knee angles in one study be related to distance and height adjustments of the pedal in another study if the anthropometric data of the subjects are not given?

Second, the instructions to the subjects are often not reported. Rees and Graham told their subject ‘ to increase the force gradually and to hold his greatest push for a few seconds ’, Rohmert says the muscle contraction lasted about one second. How did the subjects in other studies exert their strength? Did they get an immediate feedback of the attained force? Did they compete against each other, as in Hugh-Jones’ experiments?

Third, it is generally not stated what score or index the experimenter selected as ‘ maximum ’. Was it an instantaneous peak amplitude of the force curve? Was it a ‘ mean ’ force, averaged over some period of time? Was it an average of several trials?

Kroemer (1969 b) and Kroemer and Howard (1969) pointed out that these and other experimental conditions may greatly affect the results of strength measurements. There are certainly more questions than answers, both in methodology and in number of researched variables, in the area of forces applicable to foot-operated controls.

2.3. *Perception of Leg and Foot Positions and Motions*

Corlett (1965) tested perception of passive flexion and extension of the foot about the ankle joint with 8 male seated subjects, 25 to 38 years old. They placed their right foot on a pedal ' pivoted in line with the ankle joint '. The pedal was rotated by a mechanical device. Angular accelerations of 0·05–1·34 degree/s^2 were used, 8 for flexion and 9 for extension.

Corlett found recognition of joint rotation easier with large than with small angular accelerations. At low accelerations, joint rotation is recognized by means of displacement. There seems to be no difference in recognition between flexion and extension. The initial foot angle does not affect sensibility.

Davies (1966) wanted to determine the ' cue to which a subject responds when his limb is moved passively '. He placed the forearm and the foot of 6 subjects, 20 to 34 years old, on a pivoted horizontal platform so that the elbow joint or the ankle were over the pivot. The platform could be rotated with initial circumferential accelerations ranging from 150–900 mm/sec^2, measured at a radius of 39 in. from the pivot. The subject pressed a button with his left hand when he felt the platform move. Pressing the button stopped devices measuring the distance travelled and the time elapsed from onset of the motion.

Davies reported that his subjects did not respond to speed or travelled distance, but to acceleration. Movements from the ' mid positions ' (90 degrees angles) of the foot and elbow, and in downward direction (increasing foot or elbow angle) were most easily perceived.

Lloyd and Caldwell (1966) investigated the accuracy with which knee extension and flexion can be perceived. The subject lay flat on his back on a padded table. While most of the thigh was supported by the table, the knee and lower leg extended over the edge. Angle-measuring devices were strapped to each leg. The weight of the instrument and of the lower leg was counterbalanced. Forty male subjects either had to place the lower leg to selected angular positions (active positioning), or the experimenter placed the leg in a certain position and asked the subject to estimate the angle (passive positioning). In passive positioning, the subjects generally overestimated the knee angle slightly. In active positioning, the subjects were fairly accurate if the knee was only slightly bent, but underestimated the angle if the knee was distinctly flexed.

In a subsequent study (Lloyd, 1968) 210 male subjects actively positioned their lower legs to specified angles (10-degree intervals) between full knee extension and 100-degree flexion. Six different levels of brake force at the strapping device were used. Lloyd states that ' in view of previous experimental findings, the results were not as systematic as predicted '. The brake force differentially affected the direction of positioning error, but not the amount of absolute error: again, the knee angle was underestimated with distinct flexion, but overestimated when the leg was almost straight.

Corlett and Megaw (1967) investigated the role of kinaesthetic and visual feedback on very small foot motions. Sixteen sitting subjects, 18 to 35 years old, placed their right feet on a pedal pivoted ' under the ankle joint as suggested by Lauru (1957) '. The torque at the pedal was set to either 4, 13, 22, or 31 kp/cm. The amount of pedal motion, achieved by plantar flexion, was displayed to the subject on an oscilloscope with the travel amplified by factors of $\frac{1}{4}$, 1, 4, and 16. The task was to ' make minimal voluntary motions ' with the pedal.

Corlett and Megaw found that under each of the experimental conditions, the subjects 'tended to make the (required) 30 movements in approximately the same time of between 20 and 25 seconds'. Changing the torque did not significantly affect the mean minimal movement of about 0·2 degrees. By increasing the visual gain (amplification factor) from $\frac{1}{4}$ to 16, the subjects were able to reduce the mean minimal motion to about 0·1 degrees.

Drury (1967) reported on exploratory experiments in which the subject was instructed to make 'the smallest movement he possibly could'. In the first experiment, 6 male subjects (24 to 26 years old) were seated 14 in. higher than the level of the pivot of a rear-hinged pedal. The pedal was at an angle of 45 degrees with the horizontal. Inertia and torque of the pedal were 'at three levels, Low, Medium and High'. (It seems as if the inertia was up to 1·5 kp sec^2/cm, and the torque between 10 and 100 kp/cm.) Upon signals by the experimenter, the subject made 15 discrete toe-down movements under each condition. In the second experiment, with 18 male subjects (19 to 35 years old), the operator sat so that his thigh was horizontal and his lower leg vertical. The pedal, pivoted at the axis of the ankle, had its initial positions at 15 degrees above, at 0 degrees, and at 15 degrees below horizontal. In each position, the subject performed 50 self-paced toe-down motions against a constant torque of approximately 40 kp/cm.

Drury concluded that the subjects could voluntarily perform extremely small motions, which were certainly not expressions of the involuntary muscle tremor. The mean amplitude of the motions was about 0·8 degrees in the first experiment, and about 0·2 degrees in the second experiment. Inertia, torque, and initial position did not significantly affect the amplitudes.

2.4. *Transmission of Power through Rotary Pedals*

Rotary pedals, widely used with bicycles, allow the operator to transmit large amounts of energy to a mechanical system. As compiled by Wilkie (1960), champion athletes can put out approximately 1·2 h.p. over 5 minutes, about 0·9 h.p. over 10 minutes, and about 0·5 h.p. for 100 minutes or longer. These figures indicate that (except for short outbursts of energy) rotary pedals are exceptionally well suited for transfer of human energy. Cycling has been found less tiring than rotating a hand crank (Lehmann 1961, 1963; Miller 1944) which is another effective method of transfering large amounts of human energy to a mechanical system.

According to Grosse-Lordeman and Müller (1936), Hess and Seusing (1963), Karpovich (1959), Müller (1938, 1939), and Müller and Grosse-Lordemann (1937), the following arrangements allow the least tiring transfer of energies: $1 \pm 0{\cdot}3$ pedal revolutions per second, pedal radius 18–22 cm (the larger radius and number of revolutions for output of very large amounts of energy). The saddle should be above and behind the pedal axis, the line connecting saddle and axis inclined 20 to 30 degrees behind vertical. The distance between saddle and pedals should be adjusted so that the subject, keeping his trunk immobile, must fully extend his legs when trying to place his heels on the pedals in the furthest positions. Inertia of rotating masses should be large enough to maintain their rotatory velocity for at least one revolution if the feet are lifted off the pedals. Under these conditions, Müller (1967) assumes that 'ordinary healthy individuals' could transmit up to 6 mkp/s (0·08 h.p.) for hours, up to 10 mkp/s (0·13 h.p.) for about half an hour, and at least 20 mkp/s (0·26 h.p.) for less than two minutes.

2.5. *Selection and Arrangement of Pedals*

What pedal to select and how to arrange it depends mainly on the task to be performed and on the anthropometric data of the operator. If very large static forces are to be exerted, the pedal should be at about seat height, in front of the seat, and at such a distance that the leg is almost straight when the foot is placed on the pedal. In the case of large required forces, the operator must have a backrest to lean against; his thigh should be horizontal or inclined up to 30 degrees, the knee angle between 150 and 165 degrees, the angle between tibia and foot between 80 and 90 degrees.

If only small forces are required, the pedal may be lowered; force then may be exerted either by thrust of the total leg or by rotation of the foot about the ankle. For small forces, or for continuous steering tasks, or for discrete activations, the thigh still should be horizontal or slightly elevated, but the knee angle could be anywhere between about 90 and 150 degrees, and the foot angle 90 to 120 degrees.

Based on research results, theoretical considerations, and on 'common experience', recommendations for selection and arrangement of pedals have been published by Coermann and Kroemer (1968), Damon *et al.* (1966), Domey and McFarland (1963), Dreyfuss (1960, 1966, 1967), Dupuis *et al.* (1955), Hindle *et al.* (1964), Kirk *et al.* (1964), Kroemer (1966, 1967), Kroemer and Coermann (1965), Lehmann (1958), McCormick (1964), McFarland (1963), Morgan *et al.* (1963), Rebiffé (1966), Schulte (1952), Wisner and Rebiffé (1963 a, b) and Woodson and Conover (1964).

General recommendations, however, cannot solve all problems. Specific circumstances may require unusual pedals or special arrangements. Gough and Beard stated as early as 1936 (p. 11): 'Locations of the controls for positions of comfort . . . are not necessarily ones in which the maximum force may be applied'.

2.6. *Foot versus Hand Operation of Controls*

Grether (1946) investigated tracking accuracy with aircraft controls, both hand- and foot-operated. A pointer of an Autosyn indicator was caused to oscillate irregularily. Using a stick or a wheel control (from a Link Trainer) or rudder pedals (from a P-47 aircraft), subjects had to try to hold the pointer on a fixed mark. The stick was moved with the preferred hand either laterally (aileron) or fore and aft (elevator). The wheel was grasped with both hands and either rotated (aileron) or moved fore and aft (elevator). The right and left rudder pedals had reciprocating fore and aft movements; resting the heels on the floor was permitted. Efficiency (accuracy) of tracking was measured as the time during which the pointer was actually kept on the reference mark.

In the first series of experiments, the maximal control travels necessary to keep the pointer on the mark were 4 in. at the pedals, 8 in. at the stick, 8 in. of fore and aft motion and 11 in. rotation at the wheel. During 5-minute trials, 24 subjects performed their tasks more accurately with the hand-operated controls than with the rudder pedals. 'Time on target' accomplished with the pedals averaged 52% of total time. This is statistically significantly less than the scores of from 55% to 61% achieved with stick and wheel.

In a second series with the pedals and the stick, the amount of travel of both controls was equalized to 4 in. Thirty-six rated pilots performed six 2-minute tests with each control. The ' on-target time ' was 56% for the rudder pedals, 60% in lateral stick motions, and 68% in fore–aft stick motions.

In a third series of experiments, only rudder pedals were used. The maximal travel necessary to keep the pointer on target was again 4 in. The same 36 rated pilots as before were seated with knee angles of either 105, 120, or 135 degrees, respectively. No differences in tracking accuracy (about 60% on-target time under all conditions) were found to be connected with the knee angles, but the subjects felt that 120 degrees were most comfortable.

Box and Sell (1958) investigated some aspects of hand- and foot-operated master controllers of cranes. Their report does not contain data to compare the performances achieved with each type of control, but the authors recommend that a pivoted foot controller be used with an operating torque of 30–60 in. lb. The pivot should be about 5 in. forward from the back of the pedal and not more than 1 in. above or 2 in. below the pedal surface.

Jenkins (1946 a, b, c) reported on the accuracy achieved in applying static forces to rigid aircraft controls, i.e. sticks, wheels, and rudder pedals, respectively. Twenty subjects had to apply forces of, respectively, 1, 5, 10, 20, 30, 40, and 60 lb as accurately as possible to the controls. Recorded was the deviation of the amount of force actually applied from the force required. Generally, too much force was applied if small force was required, and too little was exerted if large force was requested; to the wheel, however, too much force was exerted at all levels. ' Consistency ' of force application was expressed in terms of the standard deviation of the force exerted divided by the force level required. Consistency was least at the small force levels and best at the higher force levels.

The rudder pedals were ' worked from the ankle ' with the heels resting on the floor. Jenkins found that the ' relative accuracy of performance with the feet was approximately the same as . . . with the hands, but that differences in the apparatus may be related to this finding '.

Human engineering handbooks usually contain judgements to the effect that foot operation of controls is more forceful but less rapid and exact than hand operation. These judgements generally seem to be based more on ' common ' experience than on experimental findings.

2.7. *Summary of the Literature Review*

As compared to the many investigations on the capabilities of performing tasks with the hand, surprisingly few research results have been published about the possibilities of using the feet. Even the most often investigated tasks, the speed of operation of hinged pedals, and the forces applicable to pedals, were studied under such different experimental conditions that there is no generalized statement possible that would indicate what pedals can be operated most rapidly or what forces can be applied to pedals.

While the hands of an operator may be overburdened with control tasks, his feet are often idle or perform only rather simple tasks. This is in accordance with the general tenor of human engineering handbooks that the feet are stronger but slower and less accurate in control operation than the hands. (Damon *et al.* 1966, Kroemer 1967, McCormick 1964, Morgan *et al.* 1963, Woodson and Conover 1964). Unfortunately, such a belief is neither sufficiently supported nor discredited by experimental results: there is simply not much information available.

3. Experiments Conducted

3.1. *Purpose*

Experiments were conducted to gain information on the travel time and on the accuracy of discrete motions of the right foot. The investigated motions were performed by seated subjects (*a*) in sagittal direction (fore–aft) by altering the knee angle between 90 and 150 degrees in 15-degree increments, or (*b*) in lateral direction (left–right) by tilting the lower leg 15 degrees to either side of a vertical plane at each knee angle. These motions were accomplished by moving the foot between targets arranged (*a*) in sagittal columns of three, or (*b*) in lateral rows of three, with a distance of 15 cm between target centres.

These experiments are part of a planned series of investigations on motions of the foot, of the lower leg, and of the thigh.

3.2. *Subjects*

Twenty male students took part voluntarily and were paid by the hour. No attempts were made to select certain persons except to exclude those having an impairment hindering the execution of foot motions; those with extremely large or small legs; those not willing to participate in at least ten sessions each.

Table 6 gives the anthropometric data of the subjects.

Table 6. Anthropometric data of the 20 male subjects
Dimensions taken as described in Kroemer (1969 a)

	Mean	S.D.
Subject standing		
Weight	73·7 kg	9·9 kg
Stature	176·6 cm	6·6 cm
Grip strength	52·7 kp	8·4 kp
Acromial height, right	144·0 cm	6·0 cm
Tibiale height, right	48·9 cm	2·4 cm
Upper thigh circumference, right	55·0 cm	3·9 cm
Lower thigh circumference, right	40·6 cm	3·2 cm
Calf circumference, right	36·5 cm	2·4 cm
Subject sitting		
Femoral breadth, right	9·4 cm	0·5 cm
Sitting height	92·3 cm	3·5 cm
Knee height, right	56·5 cm	2·9 cm
Buttock–knee length	61·0 cm	3·1 cm
Subject standing		
Skinfolds: Triceps	15·1 mm	4·3 mm
Juxta-nipple	13·3 mm	5·1 mm
Subscapular	14·6 mm	3·4 mm
Shoe size	9·9	1·5
Age	21·3 years	2·1 years

3.3. *Experimental Apparatus*

3.3.1. *Experimental sandal*

A sole of a standard size 9½ shoe was cut from 0·4 cm fibreboard (see Figure 3). This sole could be attached to the unshod right foot of the subject with straps

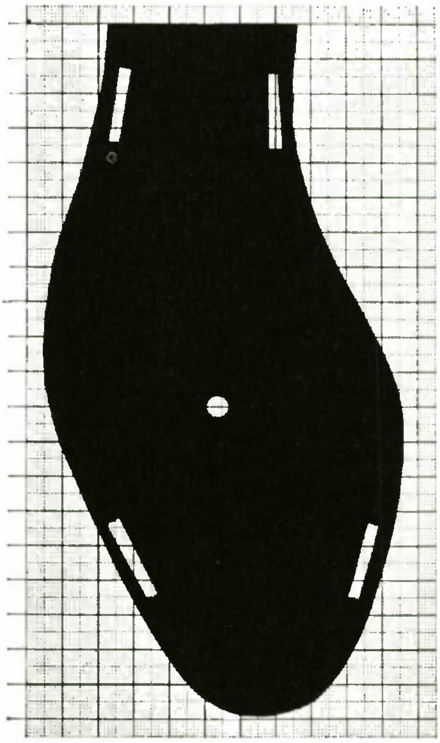

Figure 3. Experimental sandal: Partial sole made of 0·4 cm fibreboard. The sketch (on a 1 cm × 1 cm grid) shows the location of the brass spike (protruding 2 cm downward, diameter at the end 0·5 cm) and of slots for straps to attach the sandal to the subject's foot.

and velcro fasteners. A conical brass spike protruded downward 2 cm under the ball of the sole. Its blunted end had a diameter of 0·5 cm. The sandal assembly weighed approximately 120 gr.

3.3.2. *Targets*

Three targets resembling ' bull's eye ' targets of shooting contests were used. Circular brass plates, 6 cm in diameter and 0·2 cm thick, were mounted on

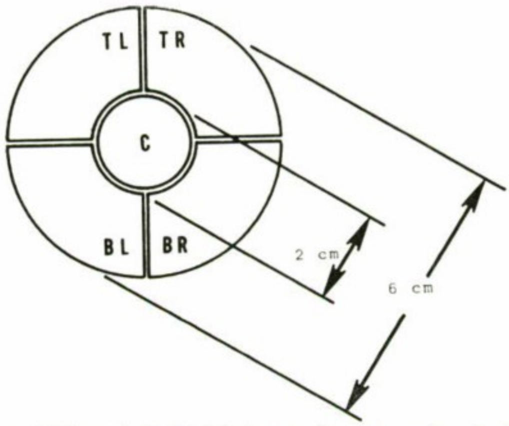

Figure 4. Experimental target, divided into a centre segment and a four-part outer ring.

fibreboard (see Figure 4). Each plate was divided in a circular centre piece (' C ', 2 cm diameter) and in a surrounding ring, subdivided into quarters. The gap between the segments was 2 mm wide. Regardless of the location of the targets during the experiments, the directional orientation of the targets was always the same: the Bottom Left and Bottom Right (' BL ' and ' BR ') segments were closest to the subject, the Top Left and Top Right (' TL ' and ' TR ') segments farthest from the subject.

3.3.3. *Target arrangements*

The targets were arranged at the reach envelope of the subject's right foot on a partial sphere, built of plywood around the knee joint ' K '. Figure 5 is a

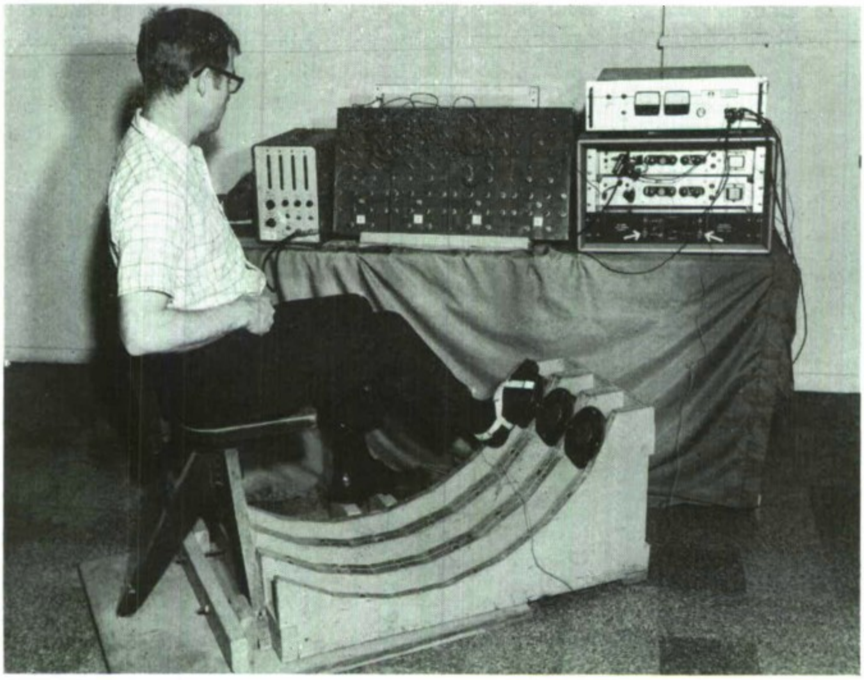

Figure 5. Total view of the experimental apparatus.

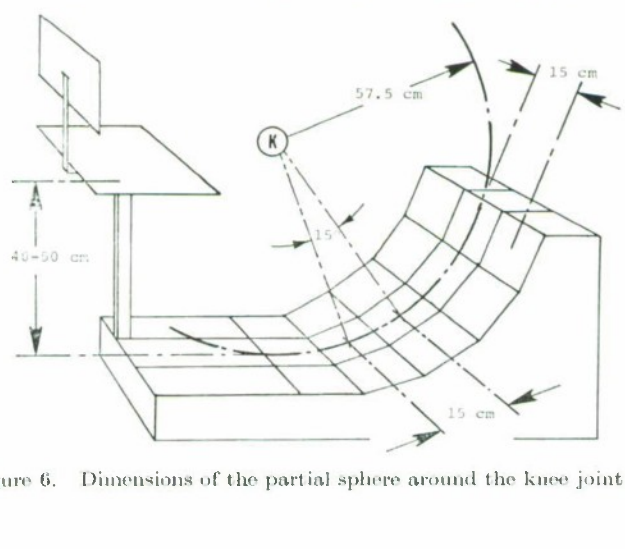

Figure 6. Dimensions of the partial sphere around the knee joint (K).

photograph of the experimental equipment, the sketch in Figure 6 gives the main dimensions.

Since the subject had to move only his right foot and lower leg, a constant location of the right knee joint was assumed. The reference point for the design of the partial sphere was the point of the sandal spike when the foot was at a right angle to the lower leg, the lower leg at a right angle to the thigh, and the thigh horizontal. With a nominal 57·5 cm radius vector from the knee joint to the spike, a 1-degree change in the knee angle corresponded to 1 cm spike travel.

From the reference point below the subject's knee, the radius vector was tilted forward in steps of 15 degrees, its pointer marking positions 15 cm apart. Each of these positions represented a target location. The highest, most forward, position in the column of five target positions was with the lower leg 60 degrees in front of vertical. Parallel to this column of five target locations, similar columns were located 15 cm to the left and to the right of the centre column. With snap fasteners, a target could be placed at each of these positions, so that the centres of adjacent targets were 15 cm (15 degrees) apart laterally or sagitally.

Figure 7 identifies the target arrangements and explains the nomenclature.

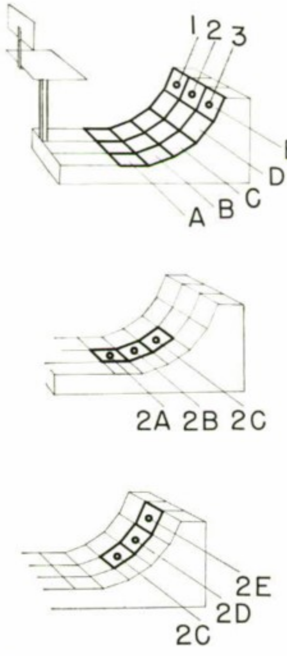

Figure 7. Target arrangements.

The letters A through E denote the lateral rows. The horizontal row A is beneath the subject's knee; row B is more forward and tilted 15 degrees towards the subject; row C is the centre row, tilted 30 degrees; row D is tilted 45 degrees; row E is the most forward and the highest, tilted 60 degrees against horizontal.

The numbers 1, 2, and 3 denote the sagittal columns, numbered from the left to the right. The middle column (2) was always in the subject's sagittal plane through his right shoulder.

The three targets were either arranged in the lateral rows A–E (upper part of Figure 7) or in the middle column 2 (centre and lower parts of Figure 7). By simple combinations of the letters and numbers, the target arrangements and even the motions between targets can be identified easily by three symbols. The first symbol indicates whether the targets are in rows (letter) or in the centre column (number 2). The second symbol identifies the start target, the third the goal target. For example:

'E 2 3': Targets arranged in the highest row (E), motion from the middle target (2) to the right target (3).

'2 E D': Targets arranged in the upper part of the centre column, motion from the highest target to the second highest.

3.3.4. *Recording equipment*

The brass spike on the subject's sandal and the brass targets served as switches in an electric circuit used to measure time and accuracy of the foot motions.

Motion time. Lifting the foot off a target (opening the circuit) started an electronic time measuring device (Beckman Universal Timer). Placing the spike on any target (closing the circuit) stopped the timer. In this manner, the time elapsing during the travel of the foot from one target to another was measured in 1/1000 sec. The experimenter recorded this time on a data sheet.

Motion accuracy. Each of the five segments of the targets was electrically connected to a separate light bulb. These light bulbs were arranged on a panel in the same manner as the segments. A lighted bulb signalled that the corresponding segment of a specific target was touched by the spike. In this manner subject and experimenter could see from which segment of a target a motion started and which segment was hit on the goal target. Using a simple combination of letters (see Table 7), the experimenter marked on a data sheet which part of the goal target was hit first by every motion.

3.3.5. *Chair*

A chair, adjustable in height as well as fore and aft, was attached to the plywood sphere. Seat pan and backrest were of polished wood, unpadded to give very little frictional resistance to the subject's motions. The seat pan was 33 cm long and 42 cm wide. The backrest was 14 cm high and 31 cm wide, its lower edge about 20 cm over the seat pan. The backrest was about 110 degrees inclined from the horizontal seat pan.

3.4. *Experimental Design*

3.4.1. *Assignment of target arrangements*

Using a table of random numbers, the experimenter assigned two of the five lateral rows of three targets (A through E, see Figure 6) to each subject. However, the schedule was so balanced that each combination of two of the five rows was assigned to two of the total 20 subjects. In addition to the two lateral rows of targets, both sagittal columns of three targets were allotted to every subject. In this manner, each subject was equally trained in lateral and sagittal foot motions.

Table 7. Symbols used to describe the position of the foot (spike) on a target

	One bulb lit (spike touches only one segment of the goal target):
C	Centre
TL	Top Left
TR	Top Right
BL	Bottom Left
BR	Bottom Right
	Two bulbs lit (spike bridges gap between two segments; i.e., touches both segments at the same time):
CTL	Centre—Top Left
CTR	Centre—Top Right
CBL	Centre—Bottom Left
CBR	Centre—Bottom Right
T	Top (Top Left—Top Right)
L	Left (Top Left—Bottom Left)
R	Right (Top Right—Bottom Right)
B	Bottom (Bottom Left—Bottom Right)
	Three bulbs lit (spike bridges gap between three segments):
CT	Centre—Top
CL	Centre—Left
CR	Centre—Right
CB	Centre—Bottom
	In addition, the following information was recorded:
M	Target missed (*de facto*, or when it took the subject 500 msec or more to move to the goal target)
T	Target touched (when the light bulbs flickered but the experimenter could not determine the exact location, or when it took the subject more than 200 but less than 500 msec to move to the goal target)
?	Question mark (when anything irregular or not expressible through the letters given above happened)

3.4.2. *Sequence of foot motions between targets*

Using a table of random numbers, the experimenter established for every subject the target from which the foot motion was to start and, if the start target was the middle one, to which of the adjacent targets the first motion should be directed. From there on, the motions were automatically sequenced to the next target or, if the end of the target row (or column) was already reached, the order was reversed. If, for example, the subject had to perform on a target row all possible start positions and motion sequences between targets No. 1, 2, and 3, are described by:

12, 23, 32, 21; 12, ...
or 23, 32, 21, 12; 23, ...
or 32, 21, 12, 23; 32, ...
or 21, 12, 23, 32; 21, ...

For every subject, the selected initial motion was maintained during all his test sessions.

3.4.3. *Test schedule*

In every test session, the subject performed on all four target arrangements assigned to him, i.e. on two of the lateral rows of targets and on both sagittal columns of targets. The presentation sequence of these arrangements was random.

As exemplified in Table 8, the subjeet first performed 40 discrete foot motions. After resting for 2 minutes, he performed another 40 such movements. Thereafter he got at least 5 minutes pause which he would spend at his convenience. During this recess, the experimenter changed the arrangement of targets.

The complete test session, 80 foot motions each on four target arrangements, took no more than one hour. The next session with the same subject was held the next day or later.

No minimal number of test sessions was prescribed, but each subject performed until his time scores under the same experimental conditions stayed on the same level. This state was reached when his mean scores of the same motion obtained in three subsequent sessions differed from each other by less than 10% of the smallest value: the mean scores used were calculated from the five shortest motion times.

Table 8. Test schedule (Sample; Subject 68–10)

FIRST EXPERIMENTAL SESSION

1.1. Lateral target row ' A ': Start on centre target (A2); first motion to the right (A23); then return to the centre (A32); from there to the left (A21); return to centre (A12). Do ten times. Rest 2 minutes. Do the four motions in the same sequence again ten times.

In abbreviated notation: A23

Five or more minutes rest.

1.2. Sagittal target column ' 2, ABC ': Start on centre target (2B); first motion forward (2BC); then return to centre (2CB); from there backward (2BA); forward to start target (2AB). Do ten times. Rest 2 minutes. Do 40 more motions.

In abbreviated notation: 2BC

Five or more minutes rest.

1.3. Lateral target row ' B ': Start on centre target (B2), move first right (B23), then return to centre (B32), move left (B21), return to centre (B12). Do this ten times. Rest 2 minutes. Do 40 more motions.

In abbreviated notation: B23

Five or more minutes rest.

1.4. Sagittal target column ' 2, CDE ': Start on centre target (2D); do 2DE, then 2ED, then 2DC, then 2CD. Do this ten times. Rest 2 minutes. Do 40 more motions.

In abbreviated notation: 2DE

End of first session.

In the following session, these arrangements are presented at random:

SECOND EXPERIMENTAL SESSION	THIRD EXPERIMENTAL SESSION
2.1. Same as 1.3: B23.	3.1. Same as 1.2: 2BC.
2.2. Same as 1.2: 2BC.	3.2. Same as 1.1: A23.
2.3. Same as 1.4: 2DE.	3.3. Same as 1.4: 2DE.
2.4. Same as 1.1: A23.	3.4. Same as 1.3: B23.

Etc.

3.4.4. *Instructions given to the subject*

The subject was instructed to sit comfortably but straight, his thighs horizontal, his right knee over the lowest target position in the centre column (2A in Figure 7). This column was to be in a sagittal plane through his right shoulder. If necessary, the chair was adjusted to achieve this body posture.

The subject was instructed to move his right foot as rapidly as possible from the centre of the start target to the prescribed adjacent target. The experimenter stressed that speed of this motion was the main objective, that the subject should not worry about the accuracy of such motions. The experimenter pointed out that achieving time scores necessarily required that the target be hit, and that training for speed would automatically train for motion accuracy.

Each motion was to start from the centre of the start target. Subject and experimenter simultaneously controlled this by observing the light bulbs on the display panel in front of the subject. The subject did not look at the targets while performing the experiments, but achieved the correct positioning of his foot by observing the light panel. Located adjacent to this light panel was the timer, enabling the subject to observe his time scores.

The subject was instructed to wait for an audible signal before starting a foot motion. The experimenter gave this signal when he had recorded the results of the previous test on a data sheet and was ready for the next test. The subject could then perform the next motion at his convenience, but did not have to start immediately.

3.5. *Results*

Twenty subjects took part, on the average, in 12 test sessions (mean 11·7; SD 2·4). The following results are based, if not otherwise stated, on the five fastest motions executed by each subject under each experimental condition.

3.5.1. *Learning*

Since the subjects had no special ' practice sessions ', the process of learning the foot motions is reflected in the recorded data. Figure 8 shows the mean (± 1 standard deviation) travel times achieved by all 20 subjects during their three first sessions, during their median session, and during their three last

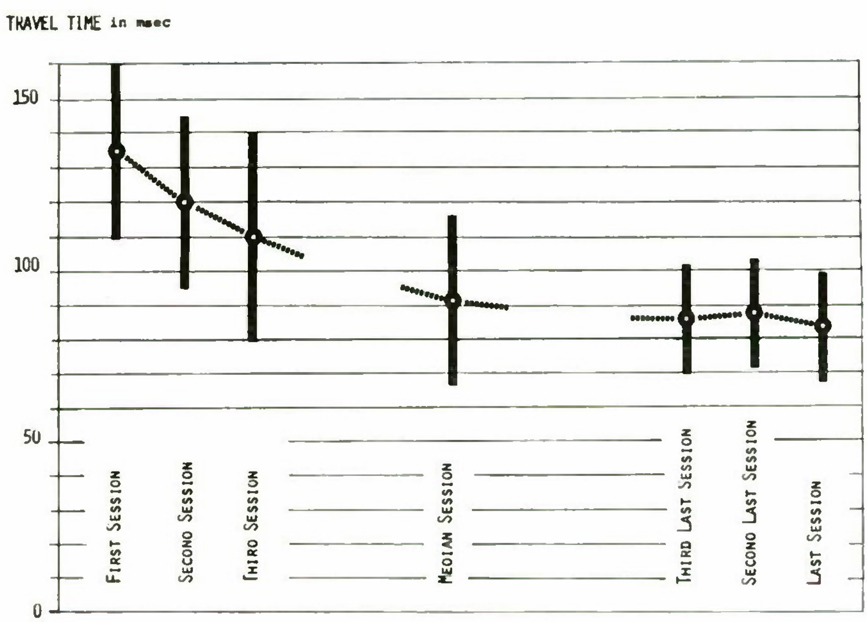

Figure 8. Performance during the first three experimental sessions, during the median session, and during the last three experimental sessions. Travel time in milliseconds (means and standard deviations) of each subject's five fastest trials of motion 2BC.

sessions while moving the lower leg 15 degrees forward from a knee angle of 105 degrees to 120 degrees (motion 2 BC). The mean travel times decreased from 135 msec in the first trial to 83 msec in the last trial. A check of the accuracy recordings did not indicate any systematic change in the segments first hit on the goal target during the course of experimental sessions. This motion 2 BC, though one of the fastest, is typical of all the motions: the travel times decreased rather steeply in the first few test sessions, while at the end of the experiments the travel times levelled off. However, no general changes in the orientation of segments first hit, or in the number of cases the target was missed, occurred in the course of test sessions.

3.5.2. *Shortest motion times*

Table 9 gives the means and standard deviations of each subject's five fastest motions under each experimental condition during his last three sessions. The mean travel times lay between 83 and 110 msec. To test whether the differences between the measured times are statistically significant, t-tests (using matched pairs) were calculated. With type I error probability

Table 9. Travel times (in msec) between targets; means and standard deviations

Target arrange-ment	Motion from/to	Last session Mean	S.D.	N*	Second last session Mean	S.D.	N*	Third last session Mean	S.D.	N*
Lateral motions										
A	12	100·72	19·31	8	103·97	20·04	8	104·87	15·35	8
	21	95·65	16·33	8	99·00	12·17	8	92·00	9·61	8
	23	99·80	20·05	8	104·52	25·70	8	104·20	19·49	8
	32	94·32	11·94	8	102·25	15·30	8	97·65	14·86	8
B	12	92·07	8·30	8	94·30	13·04	8	91·66	10·76	7
	21	89·47	6·19	8	95·40	12·39	8	93·26	6·88	7
	23	91·70	6·76	8	96·82	12·90	8	93·83	9·99	7
	32	86·45	10·93	8	92·80	11·60	8	93·34	10·86	7
C	12	85·40	8·68	8	92·30	12·34	8	92·87	19·26	8
	21	84·50	13·37	8	87·85	8·36	8	86·32	14·53	8
	23	86·12	9·28	8	91·30	11·14	8	87·45	13·76	8
	32	83·05	10·58	8	86·95	6·36	8	85·67	15·42	8
D	12	96·65	9·65	8	101·85	11·14	8	97·30	14·07	8
	21	98·15	15·02	8	103·45	19·46	8	98·57	16·28	8
	23	101·80	10·00	8	109·85	15·32	8	100·50	17·50	8
	32	98·35	15·09	8	100·17	18·10	8	97·97	17·81	8
E	12	97·85	15·55	8	99·77	18·56	8	102·70	19·35	8
	21	96·20	20·00	8	97·12	20·81	8	99·55	23·95	8
	23	97·75	19·00	8	97·57	23·11	8	97·47	20·77	8
	32	93·92	20·06	8	98·00	21·16	8	95·75	21·28	8
Sagittal motions										
2	AB	84·40	17·76	20	87·90	17·79	20	87·88	14·56	20
	BA	83·37	15·01	20	88·72	17·22	20	88·69	18·53	20
	BC	83·38	16·42	20	87·93	16·42	20	85·72	15·67	20
	CB	85·93	12·70	20	86·63	15·37	20	88·02	16·51	20
2	CD	85·54	17·44	20	86·69	16·04	20	84·96	13·67	20
	DC	89·52	15·96	20	90·08	15·61	20	89·85	15·45	20
	DE	88·17	16·86	20	90·12	15·45	20	86·37	15·70	20
	ED	93·50	16·31	20	96·63	17·02	20	93·97	13·96	20

* Number of subjects participating.

of 5% or less, the results are: (*a*) within the lateral motions: null hypothesis maintained; (*b*) within the sagittal motions: motion 2ED is significantly different from all the others except 2DE; (*c*) between the sagittal and lateral motions: the two forward motions 2AB and 2BC are significantly different from all lateral motions on row D (except motion D12) and on row E. The lateral motion D23 is significantly different from the sagittal motions 2AB, 2BA, 2BC, 2CB.

3.5.3. *Accuracy of motions*

From the data recorded during each subject's five fastest motions during the last three test sessions, answers to the following questions were sought. Are there any differences between certain motions in the frequency of hits on the centre of the target, hits on the outer ring of the target, and hits on those segments of the goal target closest to the start target, as compared to hits on the opposite side of the goal target?

No such differences were found either within the lateral motions, or within the sagittal motions, or between the lateral and sagittal motions. The ring of the target was hit about eight times as often as the centre. This corresponds to the probability of randomly hitting either the surface of the ring (100 cm^2) or the centre (12·5 cm^2).

The same questions were asked in comparing the data recorded for each subject's five fastest motions with the data recorded for the remaining (slower) motions during his last three test sessions. No differences in motion accuracy existed between the faster and the slower movements.

In up to 10% of all trials, the subjects did not hit the target within 500 msec, which was counted as a ' miss '. The frequency of missing the target was not related to location or direction of foot motion.

3.6. *Discussion of the Results*

The subjects were fully aware of the (obvious) purpose of the experiments and could freely discuss all aspects with the experimenter. (During the experiments, however, no conversation, smoking, etc., was allowed.) The experimenter took care to be neutral in the discussion of the experiments but tried to dissipate any bias of the subjects as to which experimental conditions were faster, more comfortable, etc.

The experiments required prolonged concentration on a rather monotonous task. If necessary the experimenter encouraged the subject by pointing out progress he had made. Since the subject had immediate feedback from the recording equipment on his speed and accuracy of motion, he could compete against himself by trying to surpass his previous performance. Competition against other subjects, however, did not take place since the experimenter and the subject were alone in the laboratory and the experimenter did not give away information on the performance of other subjects.

All subjects could perform the foot motions by changing the knee angle in sagittal motions and by tilting the lower leg to the sides in the lateral motions. Although the subjects lifted their feet slightly during the foot travel from one target to the adjacent, the knee did not move more than about 1 cm laterally or vertically. Thus, the assumption of a rather stationary knee joint was verified.

After only a few cautious and clumsy trials, all subjects soon won confidence and rapidly acquired speed and accuracy in their motions. No 'practice sessions' were held; 'private training' was not discovered and would have been rather difficult without access to the experimental equipment. No consistent differences in learning were obvious between locations and directions of foot motions.

The experiments were conducted to get information on the maximal speed of specific leg and foot motions and to learn whether the time consumed in these motions (and their accuracy) depended on the location of the path and the direction. The motion times are not normally distributed, but cluster at the small time values and taper off at larger times. This is at least partly due to the fact that it takes necessarily a minimum time to accelerate, move, and decelerate the mass of leg and foot—on the other side, there is no inherent limit to the slowness of a motion. The slower motion times being meaningless for this experiment, each subject's performance was measured by his five fastest motions per test session and condition. This procedure yields a reliable index of the subject's capacity to move the masses of leg and foot with the necessary accuracy as rapidly as possible.

No significant differences in travel time were found among lateral motions. Among the sagittal motions, it took significantly less time to move the lower leg fore or aft between knee angles of 90, 105, and 120 degrees, than to move the leg elevated to 150 degrees back to 135 degrees. In comparing sagittal with lateral motions, the forward motion of the vertical or almost vertical lower leg (90 or 105 degrees) proved to be significantly faster than lateral motions of the lower leg at 150 degrees. If the lateral motions were performed at the smaller knee angle of 135 degrees, however, their speed was not so clearly inferior to the forward motion of the more vertical leg. At small knee angles (90, 105, 120 degrees), no significant differences in the travel times were observed between sagittal and lateral motions.

In general, forward motions of the approximately vertical lower leg were a little faster than lateral motions of the distinctly elevated leg. Backward motions of the elevated lower leg were slightly slower than fore and aft motions of the approximately vertical lower leg. Anatomically, sagittal motions of the lower leg comply naturally with the layout of the knee joint. Lateral motions, however, cannot be effected in the knee joint, but the thigh has to be rotated about its long axis at the hip joint. Different muscle groups and mass movements are involved in the sagittal and lateral motions. The effects of gravitational forces are also somewhat different. At present, however, no further anatomical and mechanical explanations for the differences in motion times are offered.

No differences at all existed in the accuracy of motions, that is, in the segments first hit on the goal targets. Fore–aft motions of the lower leg were no more accurate than movements to the sides. Motions to the left were no more accurate than to the right, although all but one of the subjects were automobile drivers. Forward motions were neither more nor less accurate than backward movements. Accuracy was not affected by whether the foot was moved to or from the middle of the three targets.

The results cannot easily be judged against other data since none were obtained under comparable experimental conditions. The author, however, was surprised by the speed and accuracy of the foot motions, which in his opinion are competitive to some hand motions. Systems of 'elementary motion times', such as MTM, WF, REFA, etc., widely used in industry (Barnes 1963), quote 'reach' times over distances of about 15 cm for the hands that are not at all faster than the travel times of the foot motions.

Great caution is mandatory in applying and, especially, extrapolating the experimental results to, for example, the arrangement of pedals in automobiles. It must be kept in mind that the subjects sat on a very short seat pan with a low-friction surface. Their thighs were horizontal, the location of the knee did not change appreciably during the motion of the foot and lower leg. The subjects performed expected motions in a predetermined direction at an instant of their choice. The objective of the experiments was to achieve high speed of motion. Accuracy of motion was of secondary concern, missing the goal target did not bring about penalties. Other experimental parameters, other types of body posture, body support, or of foot and leg movements very probably would produce results different from the ones reported here.

3.7. *Conclusions*

Very few differences in performance existed within and between discrete sagittal and lateral motions of the foot and lower leg. After rather short learning periods, all motions could be performed with about the same accuracy, although forward motions of the vertical or nearly vertical lower leg were slightly faster than backward or lateral motions of the elevated lower leg. The travel times were very short, about 0·1 seconds. Observed differences in travel times are too small to carry much weight for practical purposes.

The results encourage further research which could lead to assigning tasks to the feet that heretofore have been considered in the domain of the hands.

TSgt Jesse Simmons, USAF, contributed essentially to the success of the experiments as assistant experimenter.

Under the direction of Dr. Herbert H. Stenson and Mr. Ronald L. Knoll, Messrs. Richard Arena, Denis Donovan, Kenneth H. Ivey and Howard Kleitz conducted about half of the experiments at the Behavior Research Laboratory, Antioch College, Yellow Springs, Ohio (Contract F 33615-67-C-1280).

The experimental equipment was set up and maintained by Messrs. Ralph E. Roberts and Noel F. Schwartz, Research Instrumentation Branch, Training Research Division, Air Force Human Resources Laboratory, WPAFB, and by Mr. James M. Campbell, Behavior Science Laboratory, Antioch College, Yellow Springs, Ohio.

The statistical analysis of the experimental data was carried out by Professor Edmund Churchill, and by Miss Margaret Marshall, Anthropology Research Project, Antioch College Yellow Springs, Ohio (Contract F 33615-67-C-1310).

The author enjoyed encouragement and help throughout planning and conduct of the experiments as well as during the analysis and reporting period by his colleagues of the Anthropology Branch, its Chief, Mr. Charles E. Clauser, and by Dr. Julien M. Christensen, Director, and Dr. Melvin J Warrick, Assistant Chief, of the Human Engineering Division, Aerospace Medical Research Laboratory, WPAFB.

The research reported in this paper was conducted by personnel of the Aerospace Medical Research Laboratory, Aerospace Medical Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433. This paper has been identified by Aerospace Medical Research Laboratory as AMRL-TR-69-57. Further reproduction is authorized to satisfy needs of the U S Government.

Cet article présente une revue bibliographique se rapportant aux opérations de commandes effectuées par le pied et décrit une nouvelle expérimentation.

Les résultats publiés ne clarifient que quelques aspects isolés de la motilité de la jambe et du pied. On a assez souvent étudié l'aspect de vitesse dans les opérations effectuées par le pied ainsi que l'aspect de force qui peut être appliquée à une pédale, mais les recherches ont été effectuées avec tellement de conditions expérimentales différentes qu'il n'est pas possible de décrire un mécanisme général pouvant être appliqué à un type de pédale. Les opinions concernant les avantages et les inconvénients des opérations manuelles comparées aux opérations exécutées par une pédale ne semblent, en général, pas basées sur des résultats expérimentaux.

Dans une expérience on a demandé à 20 sujets de sexe masculin en position assise de déplacer leur pied droit aussi rapidement que possible vers des cibles circulaires éloignées de 15 cm. La direction de ces mouvements discontinus n'avait pas un effet appréciable sur la précision du mouvement. Les mouvements vers l'avant de la partie distale de la jambe en position verticale ou presque verticale étaient légèrement plus rapides que les mouvements vers l'arrière ou que les mouvements latéraux de la jambe élevée. Tous les mouvements pouvaient être exécutés en 0,1 s environ.

Die Literatur über fussbetätigte Kontrollhebel wird zusammengefasst und über eine neue Untersuchung berichtet. Die veröffentlichten Resultate klären nur einige spezielle Gesichtspunkte der Bein und Fussbewegungen. Selbst die relativ häufig untersuchte Geschwindigkeit der betätigten Pedale und die auf die Pedale ausgeübte grösste Kraft konntennicht allgemeingültig festgestellt werden, weil sie unter verschiedenartigen Bedingungen untersucht wurden. Meinungen über die relativen Vorteile und Nachteile von Hand -und Fussbetätigung von Kontrollhebeln scheinen nicht immer auf experimenteller Grundlage zu beruhen. In einem Versuch bewegten zwanzig sitzende erwachsene junge Männer ihren rechten Fuss so schnell wie möglich über eine Strecke von 15 cm auf runde Zielpatten. Die Richtung der einzelnen Bewegungen hatte keine Wirkung auf die Treffsicherheit. Vorwärtsbewegungen des nahezu vertikalen Unterschenkels waren etwas schneller als Rückwärst-oder Seitwärts-Bewegungen des mehr waagerechten Unter-schenkels. Alle Arten von Bewegung konnten in kürzester Zeit von etwa 0,1 sec ausgeführt werden.

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