PROPERTIES OF FLUID FLOW APPLIED TO ABOVE-KNEE PROSTHESES

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An understanding of some of the key principles of fluid mechanics is necessary for full appreciation and wise prescription from the armamentarium of hydraulic and pneumatic systems which are increasingly becoming available in prosthetics. A review of the differences between mechanical friction and fluid friction will help to define the underlying principles of these fluid-controlled mechanisms. (Numerous textbooks are available for the serious student.) Then the internal structure and the possible adjustments of some specific models will be described briefly. Very shortly, the journal *Artificial Limbs* will devote a special issue to a comprehensive and detailed discussion of all the mechanisms which were studied in detail by an *ad hoc* committee appointed by the Committee on Prosthetics Research and Development of the National Academy of Sciences—National Research Council.

MECHANICAL FRICTION

Mechanical static friction is the force which resists any external force that tends to cause the sliding of one body over another with which it is in contact, as in Figure 1. It eventually reaches a maximum at which sliding is imminent. This limiting static frictional force is directly proportional to the perpendicular or "normal" force pressing the two bodies together. It is possible to determine limiting static mechanical friction by measuring the force that must be used to overcome the friction with a given clamping force. Thus, the ratio of the frictional force to the perpendicular force pressing the two bodies together gives the static *coefficient of friction*, $f=F/N$, which is related to the materials involved. Thus the static coefficient of friction is constant for any two particular surfaces, e.g., approximately 0.15 for steel on steel and 0.50 for leather on iron. By means of tables of such coefficients it is possible to estimate in advance what the friction would be between two bodies, such as a metal bar on a wooden socket.

The coefficient of friction between dry surfaces depends considerably on the nature of the surfaces. (The coefficient also is affected by their roughnesses, such as those of metals machined with a coarse or a fine tool, polished, or allowed to rust. The coefficient of friction between wooden blocks depends on the relative direction of the grains of the two blocks to each other and to the direction of potential motion.) Also, the value of static friction may be affected by the length of time the bodies are in contact. Thus the published tables of coefficients often supply ranges rather than precise values.

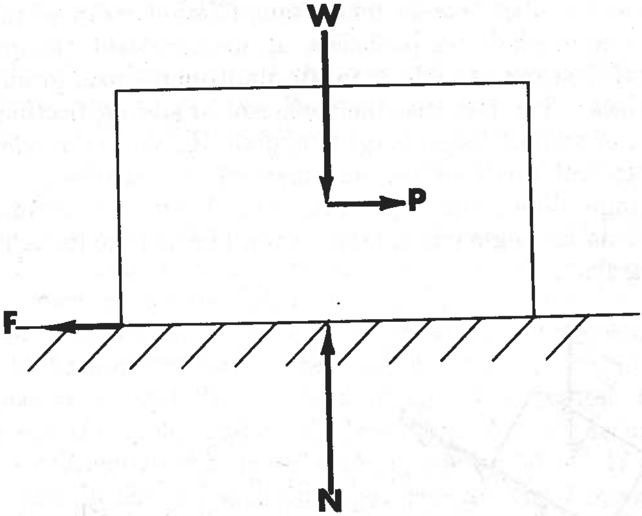

FIGURE 1. *Friction force F resists any external force P tending to cause one body to slide over another. Friction force F is proportional to force N perpendicular or "normal" to contact surfaces.*

The coefficient of friction for the same two surfaces will differ, however, depending upon whether the bodies are stationary or in motion. To start a body sliding over another requires a certain force, but to keep the same body moving at a constant speed requires only a lower force. Indeed, starting friction (also called limiting static friction or "stiction") is always greater than sliding (kinetic) friction. Thus the same two materials, without changes in rubbing surfaces, will have two different coefficients of friction: (1) a coefficient of starting friction and (2) a lower coefficient of sliding friction. Once in motion, however, the coefficient of kinetic friction remains constant even though the velocity may change, a major point in prosthetics.

The lower value of sliding or kinetic friction is important, even crucial, in many aspects of everyday life. Skidding of an automobile tire on the pavement or of a crutch tip on the sidewalk begins when the limiting static friction is exceeded, but becomes even worse as the frictional resistance drops to the sliding or kinetic value. A belt driving a machine similarly may slip relative to the pulley if overloaded. In some applications, like pulling a sled, the lower sliding friction may be appreciated.

The angle or repose, as in Figure 2, is that angle to horizontal reached by a plane surface when slipping of a second body supported on the plane is about to occur. (It can be shown that the trigonometric tangent of this angle of repose equals the limiting static coefficient of friction.) The angle of 45° sometimes attained by dry earth in an embankment implies a coefficient of static friction of dry earth on earth of 1.0. The much lower coefficient of steel on steel, though, causes slipping if the slope exceeds 8° to 10°, limiting railroad grades to even lower values. The fact that the coefficient of sliding friction is lower than that of static friction helps to explain the violent acceleration of avalanches and earth slides, once started, because the hillside must have an angle close to the angle of repose and therefore be much steeper than the smaller angle whose tangent would equal the lower coefficient of sliding friction.

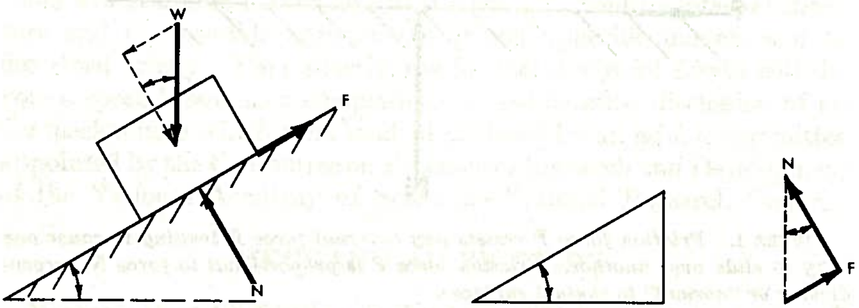

FIGURE 2. *At angle of repose, downhill component of weight **W** just balances maximum friction force **F**, while component pressing block against hill balances normal force **N**. Trigonometric tangent of angle of repose, F/N, is coefficient of friction.*

The concept of angle of repose allows ready experimental estimate of coefficient of friction or at least comparison of different materials. It also allows experimental demonstration that the coefficient of friction and the total frictional force is independent of contact area (at least if the surfaces are not grossly deformed at the areas of contact). A small oblong block of a given weight will start sliding at the same angle on a tilting plane of fixed material whether the block rests on its large flat surface or its smaller flat end.

The laws of mechanical friction between dry surfaces do not apply in the presence of lubrication. Even a thin film of grease greatly reduces the coefficient of sliding friction. The coefficient for well-lubricated surfaces may be only 5 to 10 percent of that between the same surfaces in the dry condition, and friction force depends on pressure, speed, and temperature. In fact, the properties of the lubricant, in a film thick enough to separate the surfaces completely, become crucial. (The lubricant, in a thick film and at moderate or higher speeds, obeys the same basic laws of fluid friction as do fluid-controlled knee joints.)

Belt or coil friction opposes slipping between a belt and a pulley, a band brake and its drum, or a cowboy's lariat and the saddle horn. The ratio of tensions between the two portions of the belt tangent to the cylinder increases rapidly both with coefficient of friction and with angle of contact between the belt and the cylinder, pulley, or post. Thus a strong steer can be roped and held by a light tension on the free end of the lariat after the lariat makes only a few turns about the saddle horn; the tension of the lariat is transferred to the saddle and thence to the pony.

This principle of belt friction can be applied in self-energizing brakes. An unsymmetrical arrangement of band, anchorage, and actuating lever causes the band, once in contact with the drum, to tend to be dragged along by friction forces in a direction pulling against the anchor, tightening the band still further, and increasing the normal force and the frictional drag. The greater frictional drag repeats the cycle indefinitely leading to further accumulation of friction without further force on the operating lever. If the drum tends to turn in the opposite direction, though, the frictional drag tends to slack off the brake, reducing the band tension, further reducing the friction, and so on.

The principle of the self-energizing brake may be demonstrated by twisting a pencil gripped between sharply bent fingers. In one direction, toward the fingernails, frictional drag tends to pull the fingers tighter and therefore to accumulate resistance. In the opposite direction, though, the drag relaxes the grip, so the pencil turns more freely.

The self-energizing brake principle has been used deliberately in some experimental knee locks. Some of the swing-phase friction brakes appear to include some self-energizing action—perhaps inadvertently—but the concept might be exploited more systematically.

The chief features of dry mechanical friction may be summarized as (a) dependence on the particular rubbing materials; (b) direct relationship to the perpendicular force squeezing the surfaces together but independence from surface contact area and hence from unit pressure; and (c) high static friction but lower sliding friction independent of further increases in speed. These features are useful in allowing the above-knee amputee to walk at some faster cadence than is practicable with free pendulum swing, but none of these laws of dry friction assists the amputee to change speed without further adjustment.

FLUID FRICTION

There is also a force in fluids that resists the sliding of one particle over another with which it is in contact, i.e., whenever a liquid flows, there is internal friction within the liquid. This basic fluid friction may be thought of as resistance to sliding between successive imaginary thin layers, i.e., like cards in a deck. Fortunately for control of cadence with a fluid-controlled above-knee prosthesis, the time rate of shearing or sliding is important in a fluid.

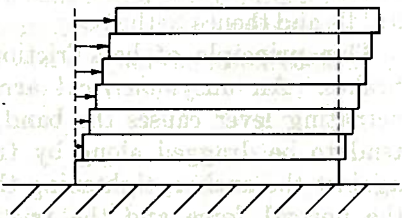

FIGURE 3. *Viscous fluid flow over a surface visualized as relative sliding of imaginary thin layers (with thickness exaggerated here for clarity). Layer next to surface remains stationary; velocity of succeeding layers increases directly with distance from surface, so friction stresses exist between layers.*

Indeed, when a fluid flows slowly through a *very smooth* straight pipe, or over a plane surface, strictly speaking there is no friction between the surface of the pipe and the surface of the fluid since the imaginary thin layer of fluid very close to the pipe does not move. There is only friction between successive very thin layers of the fluid itself, as in Figure 3. The speed of flow increases directly with distance from the wall, so each successive layer must slide over the previous one. Stresses exist between the layers, slowing the more rapidly moving layers but accelerating the slower.

For a stack of layers totaling one unit thick, the force required to keep an area of one square unit in the top layer moving parallel to the stationary wall or plane at a velocity of one unit of distance per second is called the *absolute viscosity.* The word "viscosity" is related to stickiness.

This absolute viscosity is characteristic of the particular fluid and of its temperature. Kerosene, lubricating oil, and molasses have successively increasing absolute viscosities under comparable conditions. It is a cliché that molasses flows even more slowly in January than in June; that is, absolute viscosity typically increases when the fluid is cooled. This rule is true of most hydraulic fluids, although the absolute viscosity of silicone oils changes less with temperature than the viscosities of petroleum-base oils.

This typical characteristic of viscosity to vary inversely with temperature has implications in prosthetics. In the absence of special design compensations, a hydraulic artificial knee joint will seem stiff when the prosthesis is first donned on a cold morning. Knee action will quickly become normal after the energy lost by friction during walking a short distance has become converted to heat, thereby warming the oil and lowering its viscosity. At the other extreme, vigorous use of the prosthesis on a hot summer day may overheat the oil, lower its viscosity, and thus lower the frictional resistance about the knee axis.

Under pressure of its own weight in a tank, the density of a fluid also affects its flow rate through a long, thin escape tube. Higher density will increase the pressure at the bottom of the tank, the driving force available from a given depth, and hence the speed of flow. Common instruments to measure viscosity use this principle by measuring the time for a specified quantity of fluid to escape through a standard capillary tube below the bottom of a standard reservoir. The resulting measure is related to the kinematic viscosity or ratio of absolute viscosity to density. The real densities of so-called "heavy" summer oils and "light" winter oils are nearly equal, but the absolute and kinematic viscosities of the "heavy" oils are much higher. Since a fluid of higher viscosity requires more force to slide one layer over the next at a standard speed, but the densities and consequently the driving pressures differ little, the "heavy" oil takes longer to flow from the vertical bottle through the small tube in the bottom of the viscosimeter.

Flow rate is also affected by the channel dimensions, e.g., the longer the channel, the greater the resistance to flow or the greater the pressure drop. Conversely, the greater the diameter and the cross-sectional area, the easier the flow of the fluid and the lower its resistance. A wide-open faucet, for example, allows maximum flow, but when almost closed, the faucet cuts the flow to a trickle.

Viscosity of liquids decreases with rising temperature, as we know, but increases slightly with pressure, though the latter change is not important in prosthetics. The absolute viscosity of gases, in contrast, varies directly with temperature but likewise does not change appreciably with pressure. The absolute viscosity of air, for example, rises appreciably from winter temperatures to summer heat.

The speed of flow varies with circumstances; it may be a slow oozing, a fairly rapid swishing, or a fast blast of fluid. Everyone knows that much more resistance is encountered to rapid flow than to slow. The laws affecting variation perhaps are not so obvious. The dependency of fluid flow on velocity is easily demonstrated with a hypodermic syringe, which is a simple example of a piston-cylinder device with a single orifice. The faster a person tries to push the piston, the higher becomes the resistance to flow, the higher the internal pressure, and hence the greater the force resisting the plunger motion.

Originally, experimental studies of fluid flow were made for specific conditions. Some groups studied water in small brass or lead pipes, others water in big concrete aqueducts, and still others studied specific oils at temperatures and in tubes appropriate to particular industries or scientific interests. Results seldom seemed directly comparable. An Englishman, Reynolds, studied flow in smooth tubes of circular cross section. He found that with increasing speed, flow changes its character radically. First, at slow speed in a given tube there was the streamlined laminar or viscous flow (discussed above), with each layer sliding over the next at progressively increasing speed. At higher speed, there was a random, eddying flow called turbulent, from the Latin word for disorder or crowd.

Reynolds showed, both in theory and by experiment, that many different experiments, under radically different circumstances of fluid, size, and flow rate, could be brought into a single orderly array. He merely combined into a single ratio the important properties of the fluid, the channel, and the speed of flow. In turn, new applications could be designed without expensive experiments on the exact system. (This method of combination of factors and other similar dimensionless ratios useful for various fields also allows conversion of results of measurements on scale models.)

The composite effects of the fluid viscosity and density, the channel diameter, and the speed can be combined in this ratio. Now called the Reynolds number, it is the product of the velocity, diameter, and density divided by the absolute viscosity. For fluid flow in a smooth pipe of circular cross section:

$$\text{Reynolds number} = \frac{VD\rho}{\mu}$$

where V is the mean velocity of the fluid, D the diameter of the pipe, ρ its density, and μ its viscosity, all in consistent units. At low values of Reynolds number, fluid flow is viscous with particles moving parallel to each other in a streamline fashion, as in the oozing of molasses, honey, or "heavy" machine oil. With high Reynolds number, however, turbulent flow occurs, with the individual particles moving in random, whirlpool fashion across most of the stream cross section, and only a very thin boundary layer along the wall, stationary exactly at the wall and behaving in streamline fashion just beyond it. Turbulent flow also occurs even at low Reynolds number for some distance downstream of an orifice (a thin plate with a hole smaller than the diameter of the main tube) and abrupt entrances or exits of tubes beginning or ending in the walls of larger passages or tanks. If the Reynolds number is low enough, these disturbances die out downstream, and streamlined viscous flow resumes.

There is a zone of Reynolds numbers within which transition from viscous to turbulent flow gradually occurs, though the exact value to assure one or the other form is hard to predict. Smoke from a cigarette smoldering quietly on an ash tray in a still room illustrates this transition (even though the smoke column is not confined within a tube as in the discussion thus far). Close to the cigarette the rising hot air with its smoke column moves slowly, uniformly, and in obviously parallel streams. Within a few inches, the accelerating smoke reaches a higher velocity (and perhaps spreads to a larger diameter), and this leads to a higher Reynolds number associated with instability and visible turbulence.

In viscous flow through a long tube of constant circular cross section, resistance is directly proportional to speed, or velocity. This direct relation is implied by the definition of absolute viscosity. In turbulent flow, however, resistance is proportional to velocity multiplied by itself because of the random velocity changes and the transfers of fluid and momentum between imaginary layers. Thus at low speeds, fluid friction is directly proportional to the velocity; at higher speeds with the same fluid and piping, the friction increases approximately as the *square* of the velocity. (Valves may be specially designed, therefore, to give intermediate values of the exponent of the velocity in the main pipe.)

The total pressure drop resulting from turbulent flow in a long tube increases with the length and with the square of the velocity of flow. It also depends on a "friction factor" which decreases slowly as Reynolds number increases.

So far smooth pipes have been assumed. All other factors being equal, the resistance to flow is much lower through a smooth channel than through a rough one.

Even though the fluid in contact with the wall is stationary, the wall conditions affect fluid flow. One might imagine roughnesses of the wall as hills and valleys trapping a thicker boundary layer, disturbing flow even farther out from the wall, and reducing the effective diameter of the pipe. Roughness of the pipe increases the value of the friction factor and hence increases pressure drop or resistance to flow. It is difficult to express roughness quantitatively, although the friction factor depends upon the ratio of an "average" height of the projections to the diameter. A fascinating indication of the value of an underlying principle is the use of the Reynolds number to compile on a single

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graph practically all the experimental data taken in many countries, over many years, on friction factors for various fluids flowing in smooth or rough pipes of differing materials (1, 2).

Viscous flow is typically quiet, whereas turbulent flow may be noisy. Early in the artificial limb program, these factors were considered in two experimental hydraulic prostheses for control of stance phase. Each was designed with a slowly yielding knee to give viscous flow through a series of very small but relatively long holes at relatively slow speed. Therefore each model permitted quiet descent of stairs, step over step, with the hydraulic knee control yielding or bending under load. The basic concept used numerous small passages which gave the required total flow in the viscous state, instead of a single large hole allowing the turbulent state. This design was explained by one development engineer as an attempt to keep the holes so small that the laminar or viscous flow in the boundary layer close to one wall "met" the boundary layer of the other side, with no room for a central core of turbulent flow to produce noise. The second engineer reached the same conclusion on more theoretical grounds; he attempted to keep the diameter of each hole, and thus the Reynolds number, to such low values that the viscous-flow regime was assured.

For swing phase, in contrast, H. A. Mauch developed a theory showing that resistance proportional to the square of the cadence was needed. Therefore he made the multiple parallel channels of the Model B swing control leg, described below, with channels of relatively larger diameter. In fact, he deliberately incorporated sharp-edged orifices, leading the oil from the cylinder to the channels, as well as rough walls in the channels in order to obtain turbulent flow during the rapid motions of swing phase. The noise was low enough to be shielded adequately, yet the turbulent flow assured high resistance proportional to the square of the speed. Thus theoretical concepts like the Reynolds number have very great practical significance not only for the engineer but also for the prosthetist and, most importantly, for the amputee.

Comparison of Mechanical and Fluid Friction

The significance of the major difference between mechanical friction and fluid friction is shown in Figure 4. The solid curve (with axes or arbitrary scales or units) begins with high starting friction. As soon as sliding occurs, mechanical friction is constant with velocity change; that is, even when the velocity is tripled, the sliding friction remains the same. In contrast, the broken lines show that fluid resistance begins at a negligible amount and changes when the flow rate changes. In viscous flow, the resistance is directly proportional to velocity, that is, tripled velocity corresponds to tripled resistance. In turbulent flow (expected under such circumstances as high Reynolds numbers or just downstream from a tube entrance or exit, a thin-plate orifice, or any of the usual valves), resistance to flow depends on the square of the velocity, so tripled velocity creates nine times as much resistance. This much greater resistance at higher speed would seem desirable to give the improved control of swing phase described in the previous article (3). In practice, of course, the mechanical friction of seals and the high "stiction" of doughnut-like "O" rings are combined with the fluid resistance of actual systems.

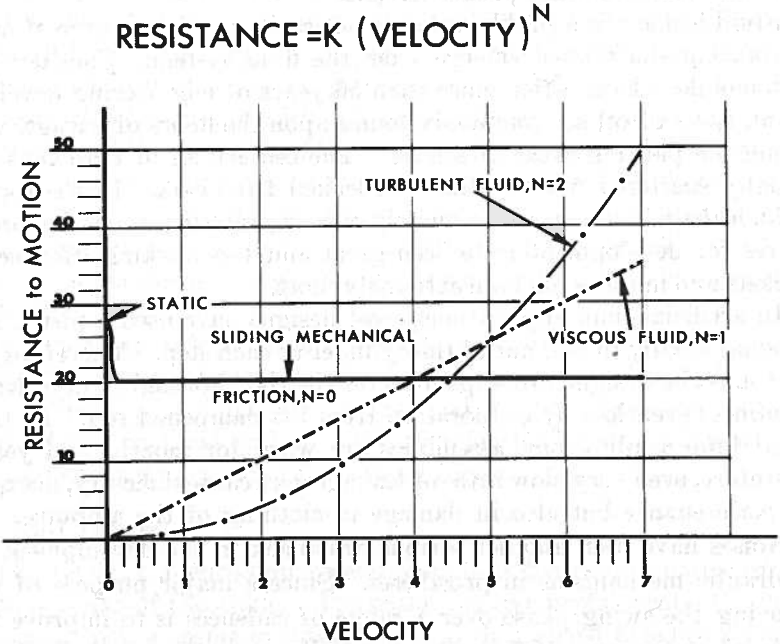

FIGURE 4. ***Variation of frictional resistance to motion in relation to velocity (arbitrary units). Static mechanical friction drops as soon as sliding begins, then remains independent of velocity. Resistance to fluid flow depends directly on velocity for viscous state and on square of velocity for turbulent state.***

DEVELOPMENT OF FLUID-CONTROLLED MECHANISMS

Fluid-controlled mechanisms have had a long history of development, as attested by the many patents to private inventors both in this country and abroad. Intensive work was done in the artificial limb program from the beginning of 1946 on hydraulic knee locks. In recent years, particularly since 1953, the development and introduction of fluid-controlled knee mechanisms to improve swing phase and hence the gait of above-knee amputees has received major attention from the Prosthetic and Sensory Aids Service.

Problems of Development

Development of fluid-controlled mechanisms has been frequently plagued by leaking hydraulic fluids, by swishing noises of the flowing fluid, by clicking noises of mechanical parts, and by control problems. These difficulties have been primarily responsible for the long delay in commercial availability of such devices.

Fluid leakage is a problem that is not easily overcome, even if only a rotating shaft must emerge from the fluid system. Consider the automobile. Even after more than 50 years of engineering development, spots of oil are commonly found upon the floors of garages and along the parking areas of streets. The centerlines of roadways are usually spattered with oil that has leaked from cars. In the rocket field, leakage has been a particularly serious problem although expenditures for development have been great and the working lifetime of rockets and missiles has been extremely short.

In artificial limb applications, most designs have used a piston rod moving axially in and out of the cylinder at each step. Therefore the seal must be designed to wipe fluid off the rod thoroughly in order to minimize even loss by evaporation from the dampened rod. In artificial limb applications, assemblies are worn for months and years, therefore, even very slow rates of leakage may cause difficulty, not only in maintenance but also in damage to clothing of the amputee.

Noises have been another serious drawback in the development of hydraulic mechanisms in prostheses. Since a major purpose of improving the swing phase over a range of cadences is to improve the cosmetic appearance of the gait, noises calling attention to the amputee would be self-defeating.

Problems of Control

Control problems, particularly serious in improving stability in the stance phase, have also offered difficulties in the swing phase. The amputee has lost not only the muscles and the bony structure which formerly provided energy and support within the absent member, but he has also lost the senses of touch and of position and his reflex control. These faculties give the normal individual his ability to react instantaneously to a wide variety of unusual walking situations, whether on uneven ground, on stairs, or at different rates of speed. Exceedingly good control is needed, therefore, to give the amputee the means of responding rapidly and safely to all kinds of walking situations. The fluid-controlled mechanisms were developed because they seemed to offer the most practical means to approach such control automatically.

FLUID-CONTROLLED PROSTHESES

In the United States there are a number of fluid-controlled swing-phase mechanisms in various stages of systematic transition. (There is a relatively orderly program to expedite new developments from the laboratory through evaluation and clinical application studies to routine clinical prescription for use by selected amputees.) The first to reach widespread use, the Hydra-Cadence has been accepted by the Veterans Administration for prescription in appropriate cases. The Dupaco Hermes unit, which has been sold commercially to private patients, and the Henschke-Mauch Model B "Hydraulik" Swing Control System are currently nearing the end of extensive clinical application studies through 16 VA clinical teams. The University of California pneumatic system is still undergoing laboratory evaluation. Various other designs have been proposed or are in the development-laboratory stage.

A general consideration of the overall design and effect of the fluid-controlled devices incorporated into these models will best illustrate how principles of fluid control are used in above-knee mechanisms. More detail on these and analyses of numerous other devices will be presented in a future issue of *Artificial Limbs.*

Hydra-Cadence

The Hydra-Cadence unit provides not only hydraulic control of the knee but also of the ankle. The manufacturer prefabricates the unit, a special foot, a cosmetic cover, a special shin guard fitted to a frame representing the shank, a metal knee block, and a cosmetic knee fairing. The entire "setup" or package is supplied to the limb facility for fitting locally to the patient.

In the Hydra-Cadence unit, shown schematically in Figure 5, resistance to knee flexion (and, therefore, limitation upon heel rise) is provided primarily by a flow of oil displaced from the bottom of the knee cylinder through a single "cadence control" throttle valve. (Flow occurs mainly to the upper side of the knee piston and also to a spring-loaded accumulator or reservoir.) The fluid resistance to knee flexion therefore depends upon the cross-sectional areas of passageways, particularly through the cadence control valve, and upon the initial factory loading of the unit with oil of the correct viscosity. (In addition, there is substantial initial knee extension bias from the accumulator.) Major changes in the fluid resistance, and thereby in the total resistance, may be effected through adjustments by the prosthetist of the variable cadence control valve. With the valve wide open, whole turns make little difference. When the valve is nearly closed, however, small fractions of a turn cause significant changes in resistance.

There is some additional change in resistance at 20° of knee flexion. At that point the descending knee piston uncovers a port in the side of the upper end of the cylinder and thus opens a bypass or connection from the bottom of the foot cylinder controlling the ankle. Correspondingly there is a smaller change in resistance to extension as the rising knee piston again covers the port. A check valve fed through a notch extending to the top point of piston travel allows some flow back through the bypass to the very end of knee extension and upward piston travel. Although these changes of resistance can be detected by accelerometer records and by some amputees, they probably are relatively unimportant in variation of resistance to knee motion.

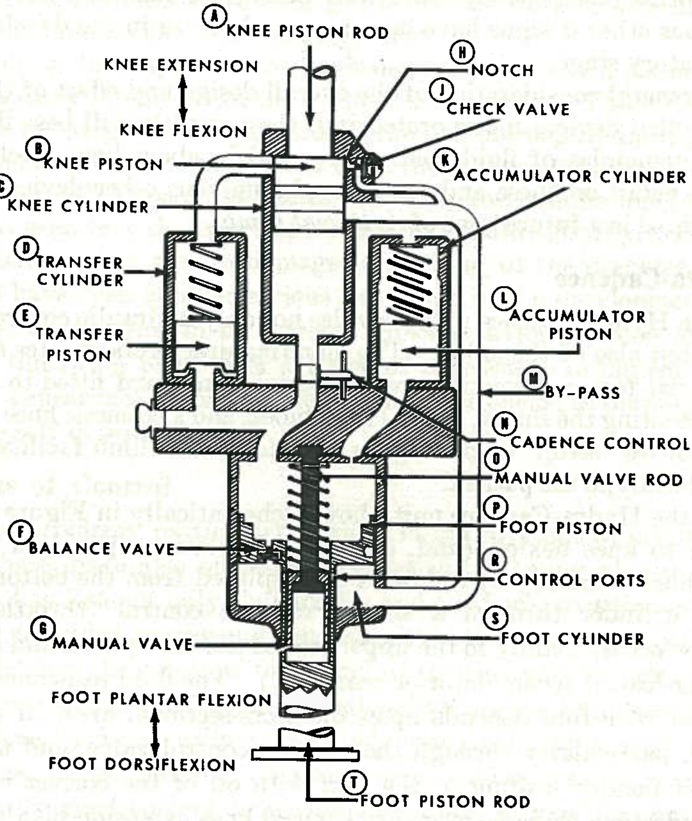

Figure 5. *Schematic diagram of Hydra-Cadence unit.*

The Hydra-Cadence hydraulic unit thus primarily provides resistance to fluid flow through a single orifice. The greatest resistance occurs at the point when the piston is moving the fluid most rapidly, somewhere intermediate in the flexing portion between toe-off and maximum heel rise, and again in the return extending portion at a position intermediate between maximum heel rise and full extension of the knee before heel contact. Thus the maximal resistance occurs considerably before knee motion is to be stopped, and the resistances to flexion and to extension cannot be adjusted independently of one another.

In the Hydra-Cadence unit, flexion of the the knee forces a piston rod (as well as the attached piston) down into a cylinder without withdrawal of an equal volume of the piston rod from the other end of the cylinder. Thus, as has been explained in the preceding paper (3), in all flexed positions of the knee an additional part of the piston rod has entered the cylinder, crowded aside some operating fluid, and displaced the surplus volume elsewhere. The spring-loaded accumulator provided in a separate cylinder exerts counterpressure upon the oil, resisting its displacement into the reservoir and tending to push it back. This counterpressure, depending upon the spring, acts upon the cross-sectional area of the piston rod to provide "kicker action" or knee extension bias. This tendency toward extension is useful in resisting flexion, and thus limiting heel rise, and in initiating extension of the knee. Later in extension, though, this continued urging toward full extension would slam the knee against the extension stop; therefore it must be overbalanced by the friction needed for terminal deceleration. When the amputee wishes to take short, nearly stiff-legged steps around a workbench, the high initial preload of this elastic extension bias, a characteristic of the Hydra-Cadence design, again is useful. Knee extension bias drops markedly when the bypass opens at 20° of knee flexion and reservoir oil moves above the foot piston.

The accumulator is also valuable to compensate for oil expansion with rising temperature. The temperature may increase not only because of changes in climate but because, as noted above, frictional work is turned into heat during rapid walking. When the temperature drops, however, the reservoir returns oil; it also supplies oil to make up for the very slow losses which still occur even with excellent seals.

The extension stop is an integral part of the unit. The piston on return to the top of the cylinder strikes the stop, so flexion-extension attitude of the knee may be adjusted from the unit. In the Hydra-Cadence system, further knee extension may be attained if the piston rod is effectively lengthened in turnbuckle fashion after loosening a lock nut with a special spanner and a wrench; such an adjustment however, is usually not indicated. The lower end of the cylinder is permanently pivoted to the frame forming the shank. The piston rod pivot is fixed in the metal knee block.

Besides transmitting the "kicker" or knee extension action of the accumulator spring to the unbalanced piston rod, the property of incompressibility of the liquid in the Hydra-Cadence system is further used to cause dorsiflexion of the ankle (toe lift) during swing phase. After 20° of knee flexion, as we noted above, the knee piston uncovers a small port near the upper end of the knee cylinder. Then oil from below a second or so-called foot piston, controlling the heel, flows up a bypass tube to enter the upper portion of the knee cylinder. Oil from the bottom of the knee cylinder and the accumulator is under higher pressure; entering above the foot piston, this oil forces the heel down but thereby lifts the toe.

During early extension of the knee, a reverse set of actions takes place, lifting the heel and dropping the toe, until the port in the knee cylinder is again covered 20° before full knee extension. (A small check valve, though, allows further flow during the remainder of knee extension but no reverse flow during knee flexion.) Oil below the foot piston is trapped whenever the knee is flexed less than 20°. Because oil is incompressible, dorsiflexion is blocked as though by a very stiff instep bumper.

Toe lift in coordination with the knee flexion during swing phase is an old idea, which Potts suggested in 1800 and used in the prosthesis he built for the Marquis of Anglesea. Unfortunately most, if not all, such designs, including the Hydra-Cadence, give maximum dorsiflexion at maximum knee bend and approximately at maximum heel (and toe) rise. At that instant the feature is least needed, as is clear from Figure 1 of the preceding paper (3).

Measurements of the ankle angle from interrupted light photographs, as in Figure 6, confirmed by direct measurements with an electric goniometer or "elgon," show considerable variations, which may depend upon the individual amputee, the hydraulic units, or the cosmetic cover. The theoretical toe-lifting action which the basic hydraulic circuit unquestionably provides therefore varies in actual practice. Figure 6 seems reasonably typical of unit function with cover removed.

Inherently, the artificial knee returning toward extension starts to return the ankle toward its neutral position. The amount of dorsiflexion remaining at the point when the toe is most likely to stub varies with individual circumstances from nearly the maximum to approximately half. Even so, *any* amount of dorsiflexion may lift the toe and ball of the foot just enough to clear certain obstacles;

"a miss is as good as a mile." Whether the ground clearance is best attained by a special ankle or by an ingenious knee mechanism is still controversial.

Ironically, in many, if not most, individuals the heel, not the toe or ball of the foot, is the point which approaches the ground most closely during midswing in ordinary walking on a level surface. In comparison with the toe and the ball of the foot, the heel passes closer to the ground later in the swing, with the knee much more nearly extended toward a more stable position. Thus, a normal individual, or perhaps an agile amputee, has a better chance to recover safely from a stumble if he scuffs the heel than if he catches the toe.

Both normals and amputees presumably balance the risk of stumbling against the costs in energy and in possible pecularities in using hip and knee motions to attain extra clearance of the foot over the ground. Dancing, for example, involves gliding over a smooth ballroom floor, indoor walking allows only for rugs and doorsills, but outdoor walking typically gives more clearance for possible irregularities in concrete sidewalk slabs, still more for cobblestones or gravel, and a great deal for rough ground.

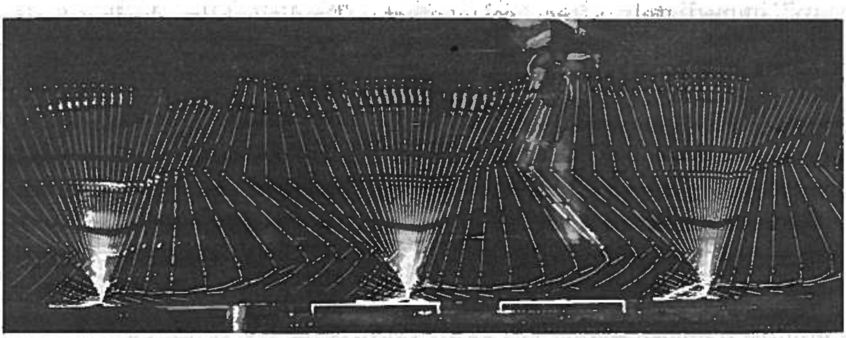

Figure 6. ***Interrupted light photo of gait of amputee wearing Hydra-Cadence. Considerable variations occur depending upon speed, amputee, training, unit, adjustments, and cosmetic cover (here removed, allowing maximum dorsiflexion).***

The toe lift actually achieved with present cosmetic covers approximates that used by normal individuals. In clinical experience many amputees report they enjoy greater safety from stubbing the toe. The Hydra-Cadence wearer clearly has another related advantage, however. The dorsiflexion associated with substantial knee flexion allows the seated amputee to bring his prosthetic foot back under the forward edge of his chair while keeping his heel and knee lower than would be possible with a conventional ankle constantly blocked against dorsiflexion. Likewise, through another feature, the seated amputee is able to plantar-flex the artificial foot when sitting with the shank inclined forward.

The neutral position of the ankle beyond which dorsiflexion is blocked can be adjusted by the prosthetist or by the amputee. This feature is sometimes used to adjust for changes to shoes with different heel height. The adjusting knob, located within the shank, is not conveniently accessible for temporary adjustment during ascent or descent of hills.

The Hydra-Cadence offers a special ankle as well as a special foot. The ankle has an exceptionally soft resistance to plantar flexion and an unusually large range of such motion compared with other devices. Its low resistance to plantar flexion under static or very slowly moving conditions is related to the rapid flow from the upper to the lower side of the foot piston as soon as the control ports are opened. External force on the foot, as at heel contact, easily produces the small upward motion of the foot piston to open the control ports. Even at faster speeds, as after heel contact in walking, the fluid frictional resistance in the passages is small, so the total effect is still equivalent to a very soft heel bumper.

In conventional as well as Hydra-Cadence prostheses, a "soft" heel-bumper action allowing easy plantar flexion had led to audible "toe slap" immediately after heel contact. Traditionally, during fitting of conventional ankle joints, prosthetists routinely tried by initial selection and by adjustment to provide a cylindrical rubber heel bumper with a compromise stiffness, hard enough to avoid toe slap yet soft enough to avoid buckling of the knee. The Hydra-Cadence mechanism does not allow any such adjustment of ankle resistance, whether spring or hydraulic, to individual needs.

Fortunately the fluid-controlled knee, fitted with optimum alignment and properly adjusted, allows walking with rapid, short, symmetrical steps. By reducing the inclination of the shank at heel contact, the amputee tends to reduce the angle through which the ankle can move just after heel contact. The momentum of the foot as it strikes the floor and the noise are consequently lessened. Most amputee wearers of the Hydra-Cadence are aware of toe slap, but only a minority complain about it.

The soft ankle resistance of the Hydra-Cadence is maintained, with the help of the flexible cosmetic shank covering, over an exceptionally large range of plantar flexion. In comparison, a rapidly rising curve of ankle moment versus equivalent plantar flexion is typical of a rubber bumper or a SACH heel cushion. Also, only a relatively limited range of plantar flexion is mechanically possible in most conventional wooden feet before contact occurs between foot and shank. The range of equivalent plantar flexion at full compression of the SACH heel cushion is also adequate for level walking but less than would be desirable for descending steep grades.

Thus the soft plantar flexion of the Hydra-Cadence ankle minimizes the usual tendency to buckle the knee at and slightly after heel contact, especially going down hill. The Hydra-Cadence therefore may be aligned with the knee bolt farther forward (consequently with less extension of the knee joint) than is customary in most prostheses. The very rigid dorsiflexion stop of the Hydra-Cadence system (until the knee bends 20°), by increasing alignment stability, may be another factor allowing unusual forward alignment of the knee bolt. Presumably such rigidity also saves energy at the ankle.

These features of soft plantar flexion and rigid blocking of dorsiflexion increase the stability of the prosthesis to such a degree that determination of alignment of the socket normally should be made directly on the Hydra-Cadence unit plus an adjustable coupling rather than on the regular adjustable leg. Probably mainly because of the stabilizing feature in the large and unusually soft range of plantar flexion of the foot, the Hydra-Cadence prosthesis has been used rather successfully for hip disarticulation amputees, and it is said to be useful for bilateral above-knee amputees.

Interrupted light studies show that a prosthetic knee joint remains abnormally extended until toe-off, not only in the Hydra-Cadence, but in various conventional prostheses. The above-knee amputee must hyperextend his hip joint, allow his spine to go into lordosis, or at least have the axis of the socket bore set in initial hip flexion (rarely provided in past years). In contrast, the human knee begins to flex late in the stance phase, but stability is maintained by delicately balanced antagonistic actions of the quadriceps and hamstring groups. Therefore the normal individual can maintain his thigh nearly vertical late in stance phase, with much less need for hyperextension of the hip or lumbar lordosis of the spine. Designers of prostheses presumably should try to balance ankle resistance, knee stability, and knee control to allow safe initiation of flexion late in stance phase.

In summary, the Hydra-Cadence knee with coordinated ankle action provides a variety of functions. Most are inherent in the design. The hydraulic resistance system emphasizes simplicity of fluid passages and bypass valving at the expense of providing maximum resistance during regions of maximum fluid flow rather than just before points where motion should stop: maximum knee flexion and full extension.

Henschke-Mauch Model B "Hydraulik" Swing-Control System

This device, in the advanced stages of a clinical application study and soon to be in commercial production, consists of a unique hydraulic system and special wood knee block and shank. The "Hydraulik"

B unit is designed to control the knee alone. It can be used in esssentially conventional types of shanks with any of a wide variety of feet, ankles, or foot-ankle combinations like the SACH. The special plywood knee block is handled in the prosthetics facility in much the same way as conventional wooden knee blocks.

Perhaps the major feature of the system is the design of its "programed" resistance, like Figure 22 of the preceding paper (3). This feature gives more hydraulic resistance approaching, first, maximum desirable heel rise and then full knee extension.

The Mauch unit, as in Figure 7, bypasses the dashpot piston with a series of parallel channels. Their entrance orifices are staggered helically and hence longitudinally along the control bushing.

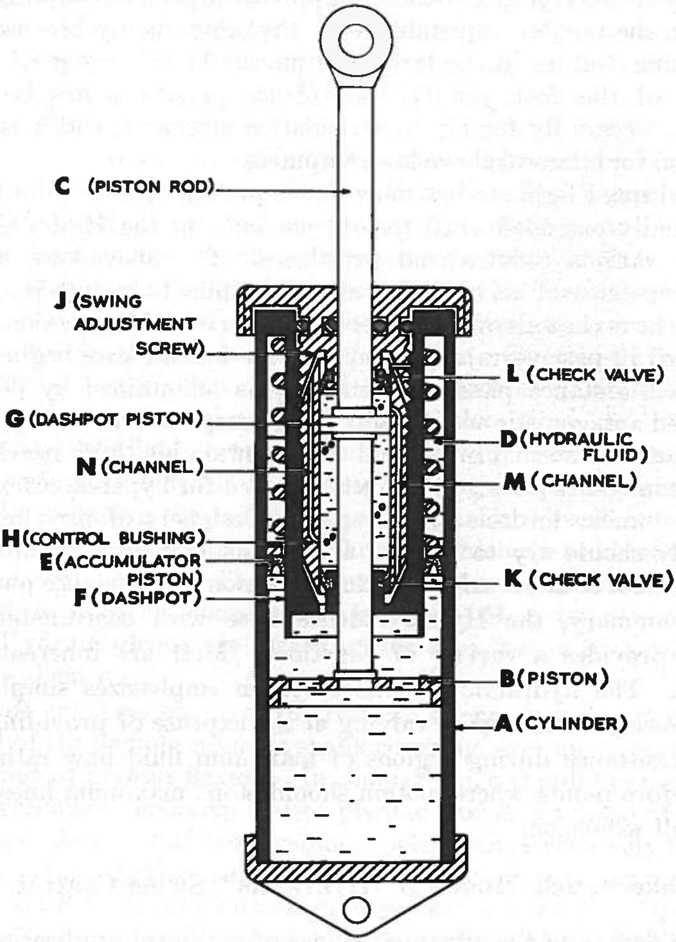

FIGURE 7. *Schematic cross section of Henschke-Mauch Model B "Hydraulik" Swing-phase Control System.*

At the beginning of piston motion all the channels are open. Later the small orifices leading to the channels are covered successively by the piston as it moves toward the opposite end of the cylinder; thus, fewer and fewer orifices and their related channels remain open for escape of the fluid. The locations and sizes of these orifices permit high resistance to fluid flow to be maintained near the end of the piston motion, when the knee is flexing and the piston moving only slowly. This design allows smooth deceleration to approach maximum desired heel rise. By correspondingly careful location of channels successively blocked by the piston moving in the opposite direction, any desired pattern of terminal deceleration can be provided near the end of the extension portion, as full extension is approached.

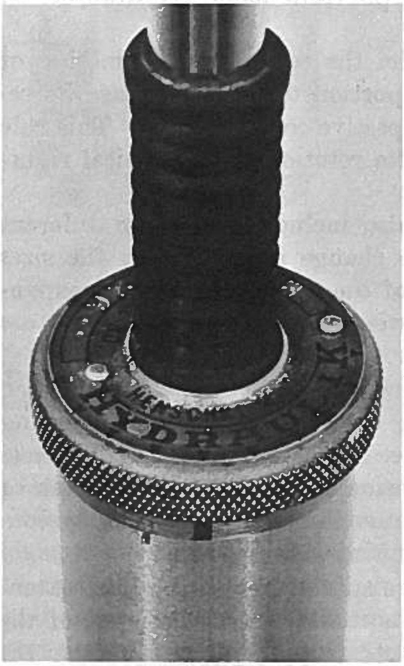

Figure 8. ***Closeup of Mauch unit showing knurled ring for adjusting hydraulic resistance, black line indicating extension resistance, and letters of trade name indicating flexion resistance by relation to black line.***

The overall resistance to fluid flow can be further varied independently for flexion and for extension. The total volume of displaced fluid, after passing the various orifices into the individual channels, must return through a cup seal (serving as a check valve) to the other side of the piston. The displaced fluid fills that portion of the control bushing whose volume is increasing as the result of piston motion. In so escaping, the displaced volume must flow through an adjustable zone between mating conical surfaces.

After taking up a special lost-motion arrangement, a single knurled or ribbed cap on the swing adjustment screw can first turn the control bushing on its threads. Such rotation regulates the size of the lower conical zone available for flow of fluid, thereby controlling extension resistance. The extension resistance is defined by the location of a black line on a lower ring (Fig. 8) showing the angular (and hence, because of the threads, the longitudinal) position of the control bushing and its lower conical portion.

After extension resistance is properly adjusted, the knurled or ribbed cap is used directly to move the upper hollow cone with respect to the control bushing. This motion adjusts the upper zone available to bypass fluid and hence changes the overall resistance to flexion. (The lost motion prevents disturbance of the extension setting.) Flexion resistance is defined by the *relative* location of the black line on the lower ring and the letters of the trade name "Hydraulik" on the knurled cap (Fig. 8).

When the cylinder is viewed from the top, clockwise motion of either the extension or the flexion portion tends to increase its respective resistance by closing the respective conical spaces. This rule is analogous to the fact that clockwise rotation of any typical right-hand screw clamps it tighter.

The Henschke-Mauch Model B also includes metals or different coefficients of thermal expansion to change automatically the sizes of the zones controlling bypassing of the fluid. Differential expansions compensate, at least to some extent, for increase of temperature and corresponding change in viscosity.

The Mauch unit may seem to balance the entry of the upper piston rod by a lower piston rod projecting out of the bottom of the swing control bushing. This rod still enters the lower cylinder, displaces fluid, and thus provides knee extension bias. The accumulator or reservoir is within the main cylinder, concentric with the swing control bushing, and acted upon by a spring-loaded piston.

The Mauch unit provides a unique adjustment of the knee extension position. A screw, with head accessible from the front of the shank, moves the lower cylinder pivot. Supporting straps from the knee bolt to the lower cylinder pivot relieve the wooden shank and the extension adjusting screw of most of the forces involved in operation of the unit.

Dupaco Hermes Hydraulic Swing Phase Control Unit

This device is now in production for commercial use and is undergoing clinical application study for possible VA use. The present model consists of a specially adapted conventional wooden knee block, an essentially conventional wooden shank, and the hydraulic system.

(Earlier models were designed for use with pylons and with plastic laminate shanks.) Any type of foot and ankle can be used. The hydraulic unit has separate and relatively independent control for the flexion and extension resistances (Fig. 9). It also has a "programed" resistance pattern using arrays of orifices to allow fluid to leave from the cylinder, shown schematically in Figure 10. The silicone fluid is relatively independent of temperature changes.

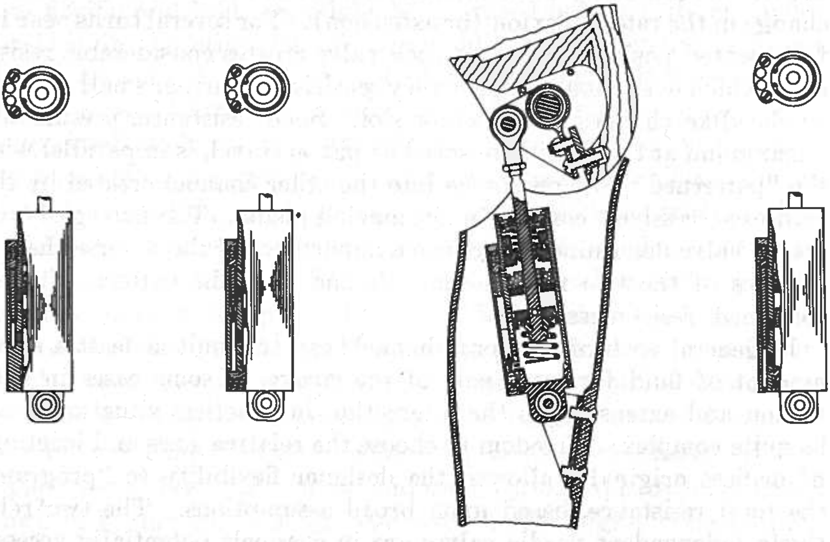

FIGURE 9. *Schematic diagrams of early model of Dupaco swing control unit. Bracket and setscrew for adjusting extension position are no longer used. Later models were adapted to wooden shanks. From* Orthopaedic Appliances Atlas, Vol. 2, *by permission.*

Four parallel vertical channels, approached by orifices of several different sizes, allow the silicone oil to bypass the moving piston. Although there are some interactions, two channels are intended chiefly to control extension so as to provide terminal deceleration just before full extension, while two other channels are primarily intended to control flexion. In turn, one channel of each pair is approached from the cylinder by a series of very small orifices which may be covered, one by one, as the piston moves toward its respective positions for maximum knee flexion or full extension. Thus the major resistance pattern is programed in small steps so that near the end of the desired motion only one or a few tiny orifices remain open to allow flow of liquid, creating great resistance. The exits from the same channel to the other side of the piston are appreciably larger holes with much less resistance, so the liquid in the channel is at nearly the same pressure as the liquid behind the moving piston. Therefore the main resistance to liquid trying to escape from the cylinder ahead of the moving piston is the pressure drop through the tiny orifices, somewhat as the main resistance to traffic on a crowded toll road is at the bottlenecks of toll gates, not at the broad plazas beyond them.

A parallel channel in each pair contains relatively large entrance and escape orifices, of small resistance, and a needle valve, adjustable by a screw on the top of the unit. The needle valve, when backed far out of its seat, offers little resistance, so even a full turn gives little change in the rate of flexion (or extension). For several turns near its fully seated position, however, each valve creates considerable resistance, which over a long range is very sensitive to further small angular or clocklike changes of the screw slot. Such resistance, presumably a maximum at the maximum speed of piston travel, is in parallel with the "patterned" flow resistance into the other channel created by the orifices successively covered by the moving piston. The setting of each needle valve determines the relative importance of the diverse characteristics of the two related channels and thus the pattern of their combined resistances.

In general each of the four channels can transmit at least a small amount of fluid for some part of the stroke, in some cases in both flexion and extension, so the interaction in practical situations may be quite complex. Freedom to choose the relative sizes and locations of orifices originally allowed the designer flexibility to "program" the total resistance, based upon broad assumptions. The two relatively independent needle valves are in channels potentially accessible only when the moving piston leaves ports uncovered. In the field, these valves give the prosthetist substantial ranges of relatively independent adjustment of resistances to flexion and extension respectively.

Flexion of the knee forces a piston rod down into a cylinder with consequent oil extrusion, as in the Hydra-Cadence and the Mauch. Instead of an extra cylinder attached to the main mechanism or an annulus about the main cylinder, the reservoir in the Dupaco system is at the top of the main cylinder. Displacement of oil is resisted by a piston loaded by a relatively soft spring.

A metal spring resisting further knee flexion comes into compression between the piston and the bottom of the cylinder. The partial equivalent of a "kicker stick," this second spring is effective in limiting the last portion of knee flexion and associated heel rise. The energy stored in the compressed spring later aids in initiating return toward extension. This spring makes contact with the bottom of the cylinder only at a large angle of knee flexion, approaching the maximum expected in normal walking. Thus it exerts its "kicker" action, supplementing high fluid resistance, near the end of heel rise, where both spring and fluid resistances are most helpful. Likewise, the short range of action of the spring in accelerating the shank toward extension prevents the serious problems at terminal deceleration that may occur with unduly strong conventional knee extension bias acting throughout the full range of knee motion. Nevertheless, this extra metal spring obviously is ineffective to "point" the prosthesis in nearly full extension to assist in taking short steps.

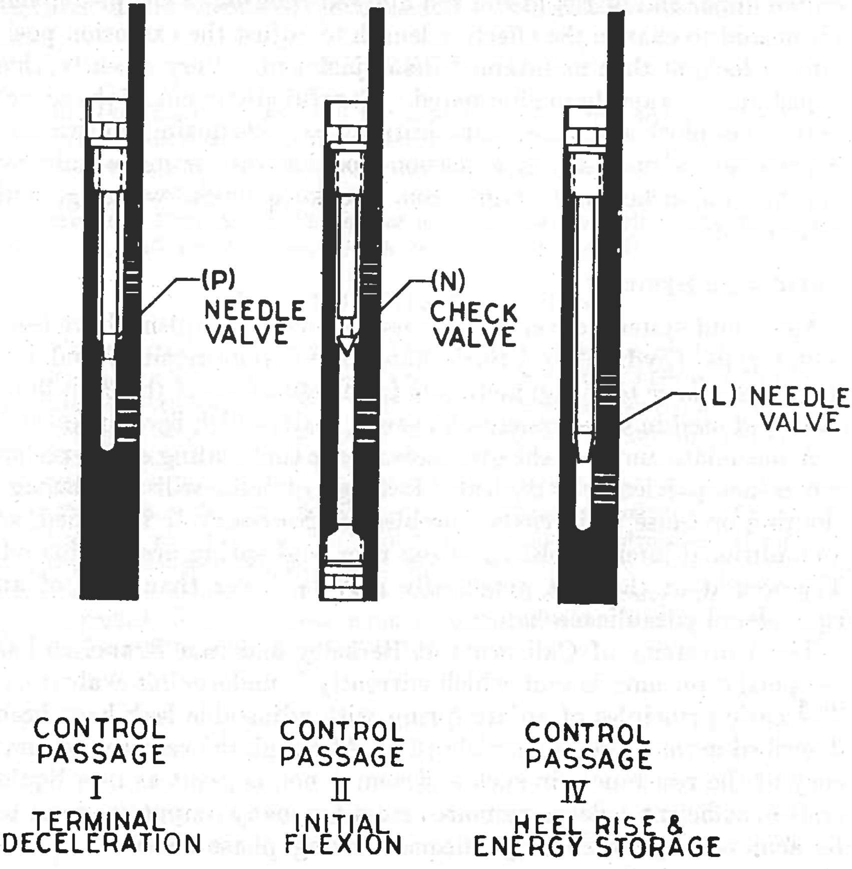

Figure 10. *Schematic diagrams of three of the four control passages in Dupaco unit. Entrance and exit ports to control passages are at different levels, so control features primarily affect specific portions of piston motion and swing phase.*

As in the Hydra-Cadence and Mauch systems, the extension stop is integral, so flexion-extension attitude of the knee is established by the unit after the ascending piston reaches its upper limit of motion by striking against a hyperextension bumper. The lower pivot of the cylinder is fixed to the shank. In an early design, an adjustment screw for knee extension was provided on a bracket pivoted about the knee bolt and supporting the upper end of the piston rod. With the pivot for the upper end of the piston rod at its uppermost level after the piston struck the hyperextension bumper, the adjustment screw for the bracket could force relative tilting of the knee block, thigh, and socket axis.

Later the pivot pin for the upper end of the piston rod was mounted in a wooden knee block, so it could not be adjusted. A screw thread on the upper end of the piston rod allowed rotation of the piston and piston rod to change the effective length to adjust the extension position; a locknut then maintained the adjustment. Very recently, this adjustment has also been eliminated. Careful alignment of the socket to the knee block and shank must initially be made during fabrication. Thereafter, adjustment of extension position can be made only by sawing the socket and thigh from the knee block, wedging, and refastening.

Pneumatic Systems

Most fluid systems developed for use as knee mechanisms have been liquid type (hydraulic). Such fluids are incompressible, and the major resistance to piston motion is from restriction of the fluid flow. The fluid used in some systems, however, is air, which is compressible.

A pneumatic unit has the great advantage that sealing of the piston rod is not particularly critical. Leakage of fluid will not damage clothing or cause maintenance problems. No reservoir is needed, so an additional internal piston, piston ring, and spring are eliminated. The weight of the unit potentially may be lower than that of an equivalent hydraulic mechanism.

The University of California at Berkeley and San Francisco has designed a pneumatic unit which currently is undergoing evaluation. The basic principles of an air spring with adjustable leak have been described in the preceding article (3). Although the velocity dependency of the resistances in such a system is not as great as in a liquid system, sufficient cadence responsiveness for many amputees seems to be achieved for reasonably adequate swing phase control.

CONCLUSION

Studies of underlying principles and comparisons with older mechanical friction control devices of the four fluid-controlled above-knee prostheses described here indicate that there are definite advantages in fluid control for above-knee amputees who need to walk at widely varying speeds. Whether these advantages overbalance disadvantages of cost and the special limitations of each system must be carefully analyzed in individual cases. All units thus far have individual limitations of minimum size of shank of the amputee and of maximum length of stump compared with the normal thigh of a unilateral. All units introduce into the practice of prosthetics the new and unfamiliar considerations outlined in the present paper. Increasing the understanding of these principles by all concerned with prosthetics clinics teams will greatly assist amputee rehabilitation. Continued development and feedback of clinical experiences should lead to further refinements of these basically desirable mechanisms.

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