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ARTIFICIAL KNEE JOINT CONTROLLER CHARACTERISATION AND CONDITION DIAGNOSIS

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Abstract: The development of the hydraulic artificial knee joint controller has significantly improved the quality of life for many people who have suffered above the knee amputations. While these devices are extremely reliable, lasting up to 3 years before servicing is required, gradual deterioration does take place. Minor deterioration of the knee controller performance can be compensated for using adjustments on the device, however, changing performance has largely been left to the user to detect qualitatively during use. Given the wide range of operating conditions that the controller may regularly be used within and the continuous usage of the device, it is not surprising that gradual deterioration of the performance is difficult to detect. Sudden failures of hydraulic knee controller units are known to occur and can result in oil leakage and loss of support, bringing about embarrassing and dangerous situations for the user. At present there is no simple quantitative test which allows for early detection of performance deterioration. The work reported on in this paper was carried out to establish clear performance characteristics for the controller. Various controller settings were used for simulated normal operating condition tests and full flexion relaxation tests. All the operating and test parameters, including performance test results are presented for a new and known to be significantly deteriorated controller. It was found that the time for the unit to return unassisted to its equilibrium position from full displacement (full flexion), varied greatly between the new and old units, suggesting a simple quantitative method for the early detection of controller deterioration.

Key Words: Artificial knee joint controller; condition characterisation; diagnostics; prostheses; quantitative test method.

INTRODUCTION: The development of the hydraulic artificial knee joint controller has significantly improved the quality of life for many people who have suffered above the knee amputations. This device has allowed for the improved functionality of leg prostheses. The ability to adjust the controller allows the user to pick settings which optimise the controller response for different user activities. The user can select settings which improve the ease with which he/she is able to climb or descend stairs, walk on a grade, jog, ride a bicycle, etc.

Given the wide range of operating conditions that the controller may regularly be used within and the continuous usage of the device, it is not surprising that gradual deterioration of the performance is difficult to detect. In general, the gradual change during regular use is too slow

for the user to notice until the performance has deteriorated significantly. Even then some users accept this performance because they do not remember the original "feel" of the device.

With an expected operational life of up to 3 years between services it would be advantageous for users to be able to assess the remaining life of their knee controller. Knowing, quantitatively, the degree of performance deterioration which has taken place would also allow users to better plan their activities, including when to have a replacement unit on hand. It could also be useful as an early warning of the increased probability of sudden and complete failure of the controller unit as performance deterioration advances.

Practitioners in the field also have difficulty determining the exact state of deterioration of the controller because they may have little or no experience with that particular unit. They are also hampered by the fact that there exist no published performance guidelines to allow comparisons against known conditions or standards.

The work reported on in this paper was carried out to establish clear performance characteristics for the controller. Various controller settings were used for simulated normal operating condition tests and full flexion relaxation tests. All the operating and test parameters, including performance test results are presented for a new and known to be significantly deteriorated controller. It is expected that tests at these two extremes of operational performance will set limits within which controllers of unknown condition can be compared. Future work will involve further testing under a variety of operating conditions and the endurance testing of several controllers from new condition through to fully deteriorated condition. This will allow complete performance characteristics to be compiled and the establishment of objective controller testing procedures

BACKGROUND: Prosthetic knees provide three functions; support during stance phase, a smooth and controlled swing phase, and unrestricted flexion for sitting, kneeling, and related activities. Hydraulic knee controllers regulate the flexion and extension motion of the artificial knee joint to achieve the above functions in an optimum manner. Hydraulic knee controllers consist of a cylinder and piston attached to the thigh section of the prosthesis above the knee and to the lower leg (shank) section below the knee (see Figure 1).

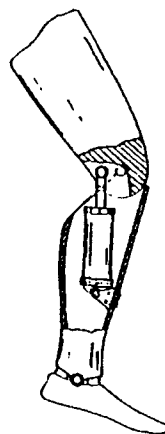


Figure 1: Artificial leg and hydraulic knee controller unit.

Knee flexion forces the piston down into the cylinder. This in turn forces fluid through a bypass channel at the bottom of the cylinder. The fluid travels upward within and around the sides of the cylinder, through a port at the top of the cylinder, and back into the central cylinder above the piston [1]. The resistance to motion provided by the liquid depends on the liquid viscosity and temperature. Silicone oil is used in most prosthetic hydraulic units because it minimises viscosity changes with temperature, thus minimising stiffness in cold weather and looseness in hot weather. The size of the oil passages and the number of passages open to allow flow also governs the rate of flexion and extension under a given load [2][3].

The hydraulic knee assists the extension process by the use of a spring. The spring is compressed during knee flexion. Energy stored in the spring during flexion is then used to push the shank into full extension during the forward swing of the leg when walking. A full description of the hydraulic knee controller operation is given elsewhere [4].

The hydraulic units can be reconditioned several times throughout their useful life, with each recondition providing approximately two million cycles or, conservatively, two years of use. The units can last as long as 20 years with the appropriate maintenance.

The Monash Rehabilitation Technology Research Unit (REHAB Tech) located at the Caulfield General Medical Centre in Melbourne, Australia suggests that prosthetic hydraulic knee units exhibit sudden catastrophic failure on a regular basis [5]. Catastrophic failure in this case means the complete failure of the unit to adequately resist flexion and retard extension and thereby provide acceptable functionality. Two of the leading manufactures of hydraulic knee controller units were contacted regarding the possibility of detecting the gradual deterioration of the performance of the units in a quantitative manner [6][7]. One of the manufacturers indicated that the user should be able to feel when the performance of the unit has deteriorated and would then return the unit for service. In their experience the units did not fail catastrophically unless used beyond their recommended useful life. The other manufacturer declined to comment.

The units that were tested were CATECH units [3]. Both units have been reconditioned approximately seven times. The 'as new' unit was recently reconditioned, while the 'old' unit came from a patient complaining of poor performance. Clinical examination of the unit failed to reveal any obvious dysfunction of the unit.

PERFORMANCE CHARACTERISATION: The action of the hydraulic knee controller unit can be modelled as a simple spring and damper system. The unit obtains its resistance to motion by the use of a viscous fluid. This allows control over the rate of flexion and extension of the knee joint. The spring provides extension assistance to reduce the amount of exertion required by the user. The behaviour of the unit may then be characterised using the rate of displacement of the piston either in flexion or in extension when acted on by a known force. The force required to move the piston at a known rate of displacement may also be used to characterise the controller unit performance. This was taken into account when setting up the experiments to assess the performance characteristics of the hydraulic knee controller.

TESTING PROCEDURE: Two types of tests were designed and conducted on an 'as new' hydraulic knee controller and on an 'old' unit. These tests are fully described in this section. The test results and a discussion of the results follows in the next section.

Flexion Relaxation Tests: The flexion relaxation tests involved compressing the piston of the hydraulic knee controller unit a known distance as would take place during knee flexion. The piston was then released and forced by the internal spring to return to the fully extended position. The displacement versus time plot generated can then be used as an indication of the controller unit's condition.

For these tests the controller unit was clamped in a vertical position. A displacement transducer was then attached. The transducer sent a voltage to a computer via an analogue-to-digital converter where the data was captured using in a data acquisition program called DTV. A program was written in DTV to allow for the appropriate sampling to be obtained. The hydraulic knee unit piston was depressed fully (flexion) and released. Data acquisition took place during the relaxation of the unit (extension of the piston). This procedure was then repeated for various settings of the unit's extension and flexion adjustments on both the 'as new' and 'old' units.

Simulated Step Tests: In the simulated step tests the hydraulic knee controller units were mounted in an Instron 8501 dynamic testing machine. The knee controller was then forced through repeated flexion and extension cycles simulating the motion induced during a typical walking cycle. The simulated step cycle is shown in Figure 2.

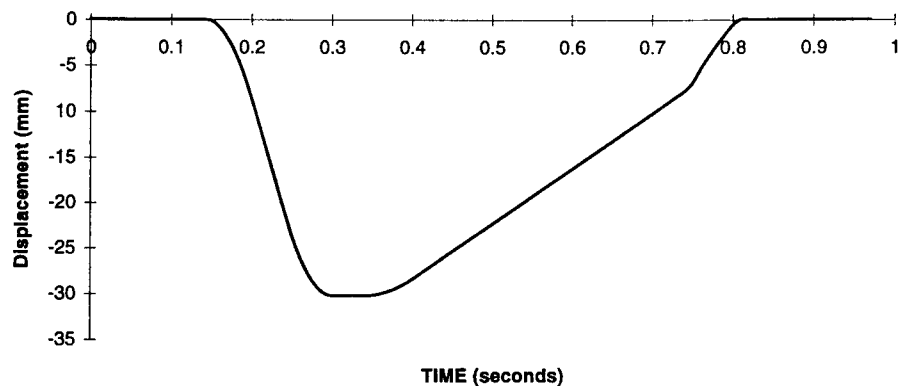


Figure 2: Typical displacement cycle of controller unit.

As can be seen from the figure, a typical step cycle can be divided into four phases. The first phase of the step is the flexion of the controller unit (knee flexion). This is a relatively short duration, high rate of displacement compression of the unit piston into the cylinder. The flexion phase is followed by a short period of time where there is no or little displacement of the piston.

The third phase is the extension of the controller unit (knee extension). This phase is of longer duration than phase one (lower rate of displacement) and ends just before the piston is fully extended. The final phase is a short duration, high rate of displacement extension of the piston to full extension. This portion of the step simulation is meant to mimic the user's flick of the lower leg into hyper-extension just before placing weight on the leg to begin a new walking cycle (see detailed description of hydraulic knee controller unit operation [4]).

The data stored by the Instron testing machine was the force required to obtain the simulated walking motion and the corresponding time values. The test on the 'as new' and 'old' unit were again performed at various settings of the flexion and extension adjustments available for each device.

RESULTS AND DISCUSSION: Due to the large number of tests conducted and the limited space available for the presentation of results, this section contains only the results from some of the tests conducted.

Flexion Relaxation Test: The results of the flexion relaxation tests are shown in Figures 3 to 6. While tests were conducted on both the 'as new' and 'old' units at most of the flexion and extension adjustment settings, only the extreme settings are shown here. The results at these settings show most dramatically the difference in performance between the two units.

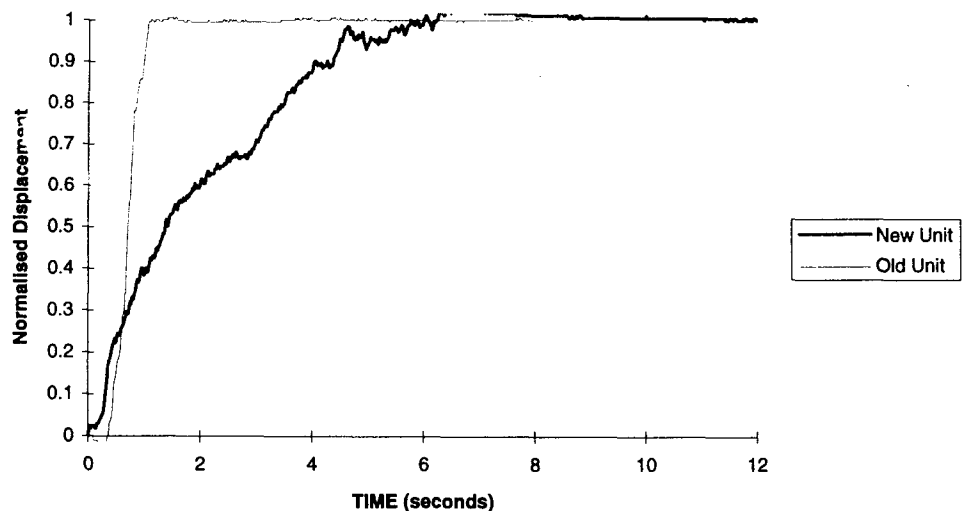


Figure 3: Flexion relaxation test at minimum flexion and minimum extension setting.

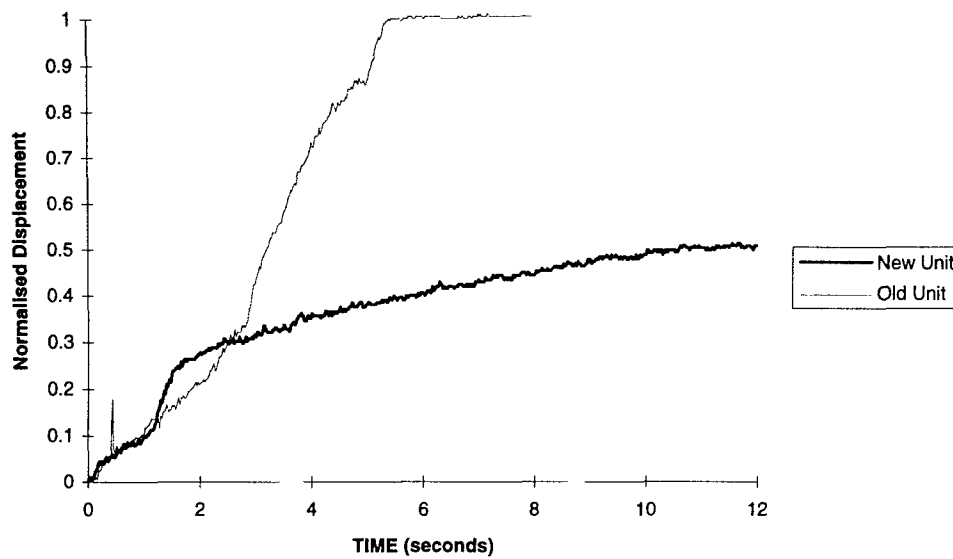


Figure 4: Flexion relaxation test at minimum flexion and maximum extension setting

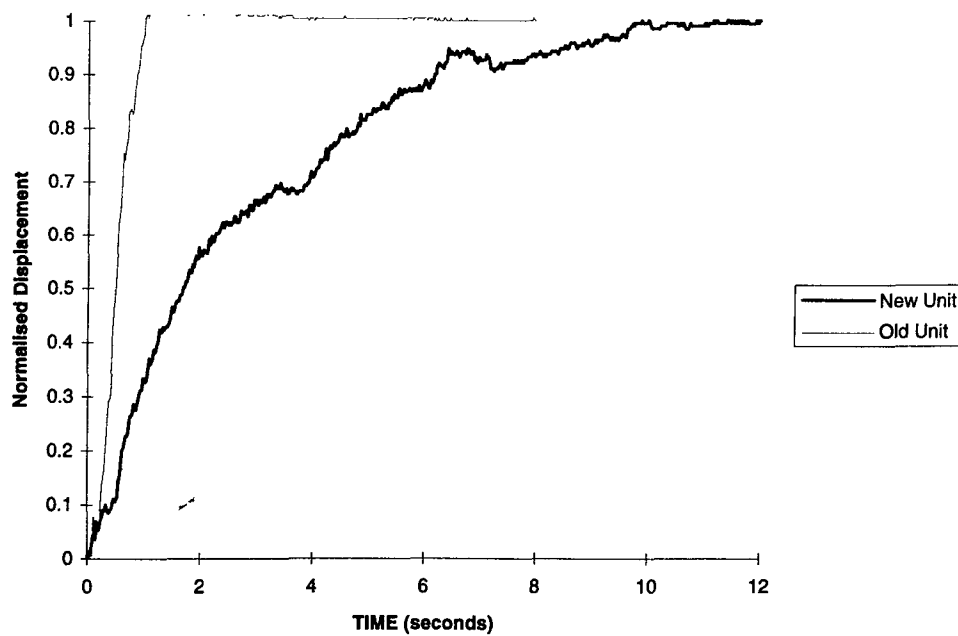


Figure 5: Flexion relaxation test at maximum flexion and minimum extension setting

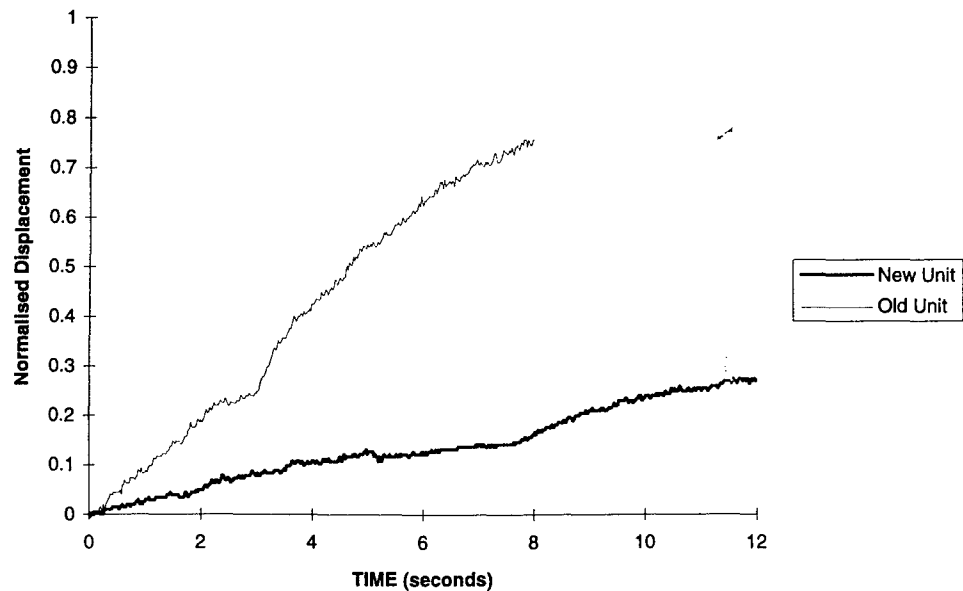


Figure 6: Flexion relaxation test at maximum flexion and maximum extension setting

In these figures it is clear that the 'as new' unit takes much longer to reach full extension at each of the different adjustment combinations shown. This result could be translated easily into a quick and simple quantitative diagnostic test for hydraulic knee controllers of unknown condition. By testing a greater population of units representing various known states of performance deterioration and other designs and manufacture's models, a series of tables or charts could be developed which would allow the performance of a controller to be quantified. It should be possible to design such a test unit for use in a clinical setting or even at the home of the artificial knee user

Simulated Step Tests: A representative sample of the results of the simulated step tests is presented in Figure 7. This figure shows the force exerted by the Instron dynamic testing machine when moving the knee controller units through the typical displacement cycle shown in Figure 2. In this plot the 'as new' unit is compared to the 'old' unit. Both units were set on minimum flexion and minimum extension. Only one plot is shown because of the similarity between plots at all the different settings.

The first point of note is that during the first test on the 'as new' unit a loud crack was heard when the unit's piston was moved through the typical step cycle. This was interpreted as catastrophic failure of the unit. As can be seen from the plot of force required to move the 'old' unit through the step cycle, the force is significantly greater than that required for the 'as new' unit. Hence, in this set of tests the 'as new' unit represents a failed unit while the 'old' unit represents a deteriorated but still functional unit. Further evidence of the failure appeared later in the test when oil began to leak from the 'as new' unit.

Two further points should be noted. The first is that there is obviously a significant difference in the force required to move the controller pistons in these two tests. Measuring the force required to move the unit piston through a prescribed displacement could, therefore, be another method of distinguishing the degree of unit functional deterioration. The second point to be made is that catastrophic failures do occur despite the manufacturers assurances that they do not.

A long term endurance test was planned for both the units but because of the failure of the 'as new' unit, it was not completed.

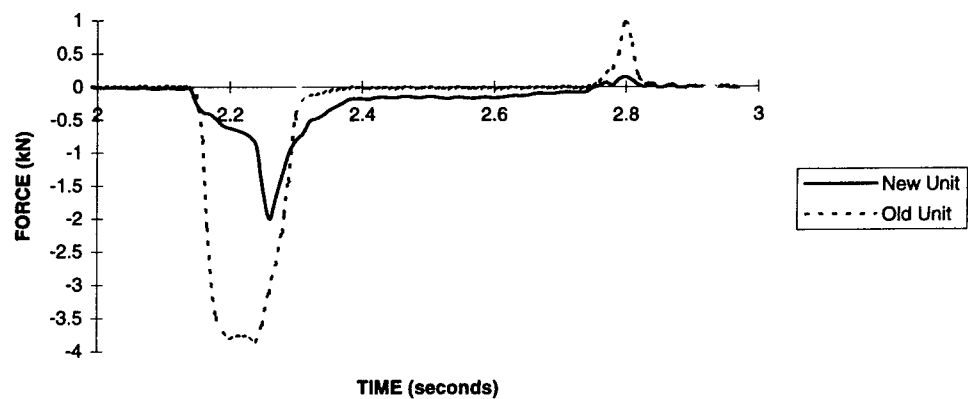


Figure 7: Simulated step test at minimum flexion and minimum extension setting

CONCLUDING COMMENTS: Hydraulic knee controllers representing 'as new' and 'old' conditions were tested using a flexion relaxation test. Knee controller units representing completely failed and deteriorated but still functional conditions were tested using a simulated step test. Both tests compared controllers which were of identical design but in significantly different operating conditions over the full range of their flexion and extension settings.

It is clear from the results presented that differences in performance can be measured and potentially used to distinguish the degree of performance deterioration of hydraulic knee controllers. Two simple methods for accomplishing this task were investigated. Noting the rate of displacement of the unit's piston under a constant load or measuring the force required to move the piston at a set rate of displacement both give clear indications of being useful tools.

The flexion-relaxation test indicates the best method for determining in a simple manner how deteriorated the performance of the hydraulic unit has become. If this test was to be designed for clinical use, it would require only a simple timing device or data acquisition program to obtain the performance data. A comparison of this data to standards representing knee controllers of known condition could then be made by the clinician or automatically using a computer based classification program. If the values were close to critical the user could then receive the appropriate servicing, if not the approximate remaining useful life of the unit could be estimated. In this way servicing could take place at opportune times, minimising lifestyle disruptions for the user and maximising the overall useful life of the unit by helping to prevent excessive damage to

units through over use. If the test and testing device were simple and inexpensive, the user would not require to go any where for testing. Instead, the user could simply test the unit and check the results in a manual at home.

Future work on this project will involve the design of a simple and accurate knee controller testing device for clinical or home use. Further testing will also be conducted on more units to check the statistical variability between units. Gradual deterioration tests should also be conducted to determine the rate of deterioration under different types and intensities of usage.

Further development work may be to design and place a built-in monitoring system into or adjacent to the knee controller unit which would be able to continually monitor the condition of the unit and give a warning if the unit operation had deteriorated excessively. This could be achieved by setting up small transducers in the knee with a microchip capable of comparing the data received from the transducers to that stored in the memory, as recommended values. This work may also lead to the design of an active controller. Such a device could possibly sense the type and intensity of use taking place, estimate the amount of unit deterioration having already occurred and adjust the flexion and extension settings automatically for the optimum performance.

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