A PARALLELOGRAM CHAIN DESIGNED TO MEASURE
HUMAN JOINT MOTION

BY

STEVEN J. COUSINS
B.A.Sc., University of British Columbia
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ABSTRACT

This work is concerned with the problem of measuring the motion of a human joint under dynamic conditions. Past and present solutions to this problem are examined in a literature search. Criteria are established for the evaluation of designs, based on one year's clinical experience with a locally built device. A parallelogram chain is chosen from generated design alternatives using the established evaluation criteria.

A prototype of the parallelogram chain is built. The chain casting has thin flexible plastic hinges. As each parallelogram scissors, unwanted translations are absorbed while three mutually perpendicular rotations pass through the chain unchanged. This allows the potentiometer motional transducers to be self-aligning with a joint. This will reduce patient fitting time and increase the reproduceability of results compared to previous devices. The chain is applicable to any large joint of the upper or lower limbs.

A test rig, simulating human joint motion, is built. Test results indicate that the parallelogram chain can record dynamic motions of walking and slow running. The chain has a definable working volume within which low error and reproduceable results can be obtained. The chain produced best results, comparable or better than those obtained by other workers, when only one of the three measuring potentiometers was aligned with the corresponding joint axis of rotation.

Errors caused by the joint simulator are explained and will facilitate redesign. The main source of measurement error is the hinge geometry and not the material properties of the chain. As a result, a new chain design is presented that should give reduced measurement errors.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>1.1</td>
<td>The Problem and Its Relevance</td>
<td>3</td>
</tr>
<tr>
<td>1.2</td>
<td>State of the Art</td>
<td>3</td>
</tr>
<tr>
<td>1.2.1</td>
<td>Approach</td>
<td>3</td>
</tr>
<tr>
<td>1.2.2</td>
<td>Past Solutions to Problem</td>
<td>4</td>
</tr>
<tr>
<td>1.2.3</td>
<td>Present Solutions to the Problem</td>
<td>15</td>
</tr>
<tr>
<td>1.3</td>
<td>Scope of this Work</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>DESIGN CRITERIA</td>
<td>20</td>
</tr>
<tr>
<td>2.1</td>
<td>Design Criteria</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>PROPOSED SOLUTIONS</td>
<td>23</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>23</td>
</tr>
<tr>
<td>3.2</td>
<td>Single Parallelogram</td>
<td>24</td>
</tr>
<tr>
<td>3.3</td>
<td>Double Parallelogram</td>
<td>26</td>
</tr>
<tr>
<td>3.4</td>
<td>Telescopic Unit</td>
<td>27</td>
</tr>
<tr>
<td>3.5</td>
<td>Parallelogram Chain</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>EVALUATION AND SELECTION</td>
<td>30</td>
</tr>
<tr>
<td>4.1</td>
<td>Evaluation and Selection</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>DETAILS OF DESIGN</td>
<td>32</td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>32</td>
</tr>
<tr>
<td>5.2</td>
<td>Material Selection</td>
<td>32</td>
</tr>
<tr>
<td>5.3</td>
<td>Hinge Design</td>
<td>33</td>
</tr>
<tr>
<td>Chapter</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>6 TEST APPARATUS</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>6.1 Test Apparatus</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>6.2 Test Procedure</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>6.3 Results</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>6.3.1 Data</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>6.3.2 Discussion</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>7 SUMMARY AND CONCLUSIONS</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>7.1 Summary and Conclusions</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>8 RECOMMENDATIONS</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>8.1 Recommendations For Future Work</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>REFERENCES</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>APPENDIX I Definition of Terms</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>APPENDIX II Typical Electrogoniometer Records</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>APPENDIX III Casting Technique</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>APPENDIX IV Summary of Manufacturer's Data Sheet of the Polyurethane elastomers</td>
<td>67</td>
<td></td>
</tr>
<tr>
<td>APPENDIX V The Attenuator Box</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>APPENDIX VI Redesigned Parallelogram Chain</td>
<td>74</td>
<td></td>
</tr>
</tbody>
</table>
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A PARALLELOGRAM CHAIN DESIGNED TO MEASURE

HUMAN JOINT MOTION
CHAPTER I

INTRODUCTION
1.1 The Problem and Its Relevance

This work is concerned with the problem of measuring the motion of a human joint under dynamic conditions. Quantitative measurements will help answer questions involving medical treatment of disabled people. The motion records of patients can be compared to those of normal people for initial assessment and later compared to themselves to measure changes due to disease, disability and treatment. The motion measurements will help to:

- decide initial physiotherapy (rehabilitative treatment),
- determine the effects of physiotherapy,
- devise new physiotherapy techniques,
- decide when to brace a joint (add external support),
- determine the effects of bracing, before and after,
- design new braces and improve old ones,
- aid a doctor's decision to operate (artificial joint replacement),
- determine problems with the implanted device,
- design new and improved implants.

1.2 State of the Art

1.2.1 Approach

Electrogoniometry* measures motion using potentiometer transducers in direct patient contact. There are remote sensing motion monitoring devices using cine film, television, and low energy x-rays but the data obtained must be reduced to useable form, eg., numbers, graphs. Electrogoniometry gives direct graphical results.

* "electro" refers to the potentiometer motion transducer and "goniometry" means angle measurement.
1.2.2 Past Solutions to Problem

The fifteen year history of electrogoniometry can be summarized by four research groups' activities:

1. Karpovich and coworkers (1959 - 1965) initiated electrogoniometry and did many basic studies (References 1 to 6). The "elgon", as he called it, consisted of a potentiometer and two thin metal bars, one bar attached to the casing and one bar attached to the shaft of the potentiometer. By strapping one bar above and one bar below the joint, and aligning the shaft of the potentiometer to the joint axis of rotation*, the motion of the joint in that plane could be measured. What is recorded is the voltage output of the potentiometer, which is proportional to the angular rotation of the joint. (See Figure 1.)

* See Appendix I for definition of terms marked with asterisks.
Flexion-extension* of the hip, knee and ankle joints of normal individuals and many disabled people were measured during various activities (including swimming).

The use of electrogoniometry in a routine clinical way was proposed by Karpovich and Tipton in their article "Clinical Electrogoniometry" in 1964.

The work of Karpovich and coworkers was significant but limited, since:

(a) only the flexion-extension motion could be measured at a joint; internal and external rotation* and adduction-abduction* were not measured; nor was valgus-varus*;

(b) data was considered from, at most, the hip, knee and ankle of one leg only. The effects of the other leg on the instrumented leg were not considered;

(c) since the devices were not self-aligning, guesses as to the alignment of the potentiometer with the joint centre of rotation had to be made each time the device was strapped to the patient. Misalignment of a potentiometer with a joint increases the possibility of motion between the device and the patient, a major source of error in electrogoniometry. The problem is that no matter how carefully the single axis of the potentiometer is manoeuvered, it will never be aligned with a polycentric joint such as the knee.

These last problems can be clarified with the aid of Figure 2. A rigid bar in the shape of a T is rotating in space. A line on the T, ab, rotates through an angle of 45° in moving from position ab to a'b', the same angle that the part of the T that is attached to the centre of rotation moves through. The points on the line ab must also translate through space because
they are not sitting at the centre of rotation. For example, point a must translate amount x over and y down as it moves from position a to a'. If a shaft of a potentiometer were mounted at the centre of rotation shown, the true rotation would be measured. If the centre of rotation moved from under the potentiometer or if the potentiometer shaft was located at point a, true rotation would not be measured; the off-axis translations would interfere with the measurement. If the potentiometer in Karpovich's device was not aligned with the joint axis of rotation, forces would be generated between the patient and the device because the off-axis translations would be constrained by the thigh and leg strap mounts (A and D of Figure 1). Because this device is not self-aligning, that is, does not automatically absorb any off-axis
translations, two errors occur:

(a) Direct error - the potentiometer does not give true rotations.
(b) Indirect error - the constraining forces imposed on the patient by the device (due to misalignment) affect the motion pattern to be measured.

2. Johnston and coworkers (1969 -1972) did the first electrogoniometric studies of three mutually perpendicular rotations occurring at a joint (References 7 to 11). The potentiometers (Figure 3) were aligned with the axis of rotation of the joint except for:

(a) Internal-External Rotation -
Since this axis was internal to the body where a potentiometer could not be mounted the potentiometer was located along the leg and an approximation of the motion was measured. Later, computer studies showed how this error could be corrected, given the location of the device relative to the joint. Their conclusion was that the larger the angular rotation, the larger the error.

(b) Abduction-adduction or Valgus-varus -
They chose to locate this potentiometer on the side of the leg, displaced away from the real axis of rotation. By attaching a long, thin rectangular shaped rod to this potentiometer and allowing this rod to telescope through the lower or distal leg attachment, any translatary movements generated by being off-axis were absorbed by the sliding rod. Thus, true abduction-adduction was measured.
Figure 3. Schematic drawing of Johnston's electrogoniometer

Johnston and coworkers improved upon the work of Karpovich, but their solution was also limited:

(a) although three perpendicular angular measurements were attempted at the knee and hip, the measuring device was not self-aligning and had to be positioned on the patient each time it was used.

(b) because the measurement of internal-external rotation was approximated using a potentiometer aligned parallel to the rotational axis (the location of this axis cannot be readily found), an error that varied with the degree of rotation was occurring.

(c) from their computer study some of the reported errors were (for motions at the hip):
Motion          | Error
---             | -----
Flexion-extension | 14.4%, 13.45°/93.45°
Internal-external rotation | 18.8%, 5.23°/27.76°
Abduction-adduction* | 6.2%, 1.45°/23.54°

*The low error is because the electrogoniometer is self-aligning in the measurement of abduction-adduction motion.

3. Lamoreux (1970 - 1971) has extensively tested simultaneously, the joints of the leg of one normal subject walking. (Reference 12). An external hip analog was built consisting of a frame that attached to the pelvis, could be adjusted so as the movements of the hip were "duplicated in the external joint system by three revolute joints connected in series."

Thus the potentiometers located at these pivots record flexion-extension, abduction-adduction and internal-external rotation at the hip. At the knee and ankle, see Figure 4, he used a self-aligning parallelogram linkage; this parallelogram linkage can measure any two out of "the three components of an arbitrary rotation in the three dimensions", absorbing the third rotation in the movement of the linkage.

The action of the device is as follows:

(a) Measurement of Flexion-extension -

Figure 5 shows the side and front views of an equivalent linkage to that of Figure 4, that will allow flexion-extension measurements to be made. Pivot H is "rigidly" attached to the leg and represents the potentiometer of Figure 4, E. This can be done, since the action of the potentiometer is in a plane perpendicular to the flexion-extension axis, e.g., perpendicularly mounted with respect to potentiometer B. As the leg flexes or extends, pivots F, G and H allow the
Figure 4. Schematic drawing of Lamoreux's parallelogram linkage

Figure 5. Lamoreux's parallelogram linkage modified for measuring flexion-extension at the knee (See Figure 4 for letter code)
linkage to straighten or bend, thus absorbing any translatory movements that occur. However, if any rotatory movements occur between the thigh and leg cuffs, (what is to be measured) the parallelogram I will transmit the rotation to bar J, thus rotating the shaft of the potentiometer located at K.

(b) Measurement of Internal-external Rotation -

Figure 6 shows the side and front views of an equivalent linkage to that of Figure 4 that will allow internal-external rotation of the leg to be measured.

Figure 6. Lamoreux's parallelogram linkage modified for measuring internal-external rotation of the leg (See Figure 4 for letter code)

Pivot F is rigidly attached to the thigh and replaces the potentiometer B of Figure 4. This is valid since potentiometer B is mounted
perpendicularly to potentiometer E and therefore cannot cause a rotation of potentiometer E. As the leg internally or externally rotates, any translatory movements will be absorbed by the linkage through a combination of parallelogram I pivoting or "scissoring" and motion in pivots F, G and H. For example, if the potentiometer at E translates forward, parallelogram I will scissor thus shortening the distance between pivots F and G. However, this shortening is accommodated with a corresponding hinging action at pivots F, G and H. If any rotatory movements occur between the thigh and the leg, the parallelogram I will transmit them through bar L to the potentiometer at E, thus recording the desired movement.

Lamoreux's self-aligning parallelogram linkage was a major step forward in electrogoniometry. The problems of aligning a single axis potentiometer with a multi-axis joint were minimized and the resetting errors, in measurement and reproduceability were greatly reduced. But Lamoreux's electrogoniometry had its limitations:

(a) the overall device was built (by choice) to study normal people and is not meant for routine clinical use. Its weight was about 3.5 Kgs or 7.5 pounds, quite encumbering for most disabled people. The hip analogue had a cylindrical cuff around the thigh (for internal-external rotation measurement) which would make use by a knocked-kneed person (valgus deformity) impossible.

(b) the hip analogue was not self-aligning. The potentiometers had to be visually aligned with the estimated joint location using surface anatomical features; reproduceability was dependent upon the skill of the user.
(c) To obtain three perpendicular rotations at the ankle, two of the self-aligning parallelogram linkages had to be used. If three rotations are to be measured this would be a bulky device to do it with.

(d) The accuracy of measurement of the parallelogram linkage on its own was not established but the overall measurement accuracy of the device on the subject was estimated (it is not explained how). The "measurement precision" varies from $0.5^\circ$ in $65^\circ$ knee flexion (0.8%) to $4^\circ$ in $16^\circ$ rotation (25%) to $4^\circ$ in $8^\circ$ of pelvic rotation (50%).

4. Kinzel and Hillberry, (1970 - 1971) have proposed a system for measuring all six possible movements between the bones that comprise a joint, that is, three translations and three rotations. Their device (References 13, 14), which has experimentally been pinned to dog legs, uses a space linkage with six potentiometers attached, Figure 7.

The six recordings obtained do not relate to the standard classification of movement, that is, flexion-extension, abduction-adduction, and internal-external rotation. To get the standard movements from the data, a digital computer is necessary for the data reduction. Kinzel and Hillberry mention these points:

(a) "If four of the potentiometers would become parallel during some phase of the motion, in that position the linkage would not accurately follow the joint motion".

(b) "Care must be exercised when the linkage is built in order to eliminate "play" due to tolerance build-up in the linkage joints."

(c) "A digital computer is almost mandatory. The use of the space
mechanism measurement system is obviously not warranted if the potential accuracy of the space mechanism cannot be used."

Figure 7. Schematic drawing of Kinzel and Hillberry's space linkage

Kinzel and Hillberry's space mechanism is a valid approach to the measurement and self-aligning problem. However, the use of a digital computer severely limits its widespread use clinically. Measurement of all six degrees of freedom at a joint may end up to be functionally quite significant. Initially however it would seem adequate to measure the three perpendicular rotations (grosser movements than the three translations) on each of the lower
limb joints of both legs simultaneously. It is the author's opinion that measurement of the interdependence of these motions during functional activities and the effects of disease and subsequent treatment on this interdependence will be as or more significant than individual joint studies. The attachment of an electrogoniometric device to a patient (beyond the scope of this work) must be faced eventually by all workers in the electrogoniometric field. Kinzel and Hillberry barely touched on this area but use of pins into bone, being practical with dogs, is impractical for human patients. The use of small suction cups and small amounts of spray-on medical grade adhesives over boney landmarks along with angular attachment brackets which, when tightened down, deform and grip the flesh, preventing rotary movements, may lead to some answers.

1.2.3 Present Solutions to the Problem

Jim Foort, Orthopaedics, UBC, and later the author, designed, built and tested an electrogoniometer, Figure 8, which monitors the movements of the knee and ankle:

Figure 8: The electrogoniometer used at the Canadian Arthritis and Rheumatism Society's Vancouver B.C., Canada centre.
(a) flexion-extension (knee)
(b) valgus-varus (knee)
(c) inversion-eversion (ankle)
(d) plantar-dorsiflexion (ankle)

Although this device has some of the drawbacks of the equipment used by previous researchers, a year of clinical experience was obtained that allowed Foort and Cousins to:

(a) define the criteria necessary for the evaluation of existing and new electrogoniometric devices,
(b) quantitatively assess patient function under dynamic conditions,
(c) gather enough information of arthritic joint movement to design a new arthritic knee brace (Reference 15).

Typical patient records from this device can be seen in Appendix II.

Current work on electrogoniometry includes:

(a) Dr. R. Jackson's work at the Toronto General Hospital which involves using an electrogoniometer with six potentiometers for studying the knee in the clinic. The device is very similar to that of Kinzel and Hillberry.
(b) At London, England, Gordon Judge an Engineer with the Biomechanical Research and Development Unit, has designed a mechanism (at the balsa wood model stage) "for maintaining output rotation parallel to input rotation but absorbing all translation movements" in three dimensions (Reference 16). Gordon Judge's drawing of this is shown in Figure 9. The mechanism consists of two double parallelograms mounted at right angles to one another one vertically and one horizontally. A double parallelogram, two
Figure 9. Gordon Judge's double-double parallelogram mechanism single parallelograms put together, has the same characteristics that Lamoreux's single parallelogram plus a hinge had. Any translations in a plane can occur unrestrained (to the limit of the link lengths), but as soon as a rotation is imparted to one end of the system, the rotation is transmitted through unchanged to the other end of the system, where it can be used to rotate a potentiometer shaft. The central bar of the vertical parallelogram "has to be external to avoid fouling the other central cross-member" of the horizontal double parallelogram. To complete the action of the
mechanism, pivoting is allowed through the input/output shaft
mounts at arrows marked A, B, C, and D. The three potentiometers
used with this mechanism can be mounted as a cluster above or be­
low the device as Gordon Judge suggests, or split, two above, one
below, in a similar manner to Lamoreux's.

This "double-double parallelogram" is an excellent concept. It
allows three perpendicular rotations to be measured at a joint independently
(within the limits of the link lengths) of the location of the center of ro­
tation of the joint or how this center moves (self-aligning). The device
could be designed as a module that would fit any or all of the lower limb
joints on both legs, hip, knee and ankle.

A few problems with the device may be:

(a) About 20 hinges or pivots are present in the design and care
will have to be taken in its manufacture to prevent free-play. Re­
design is necessary to reduce the number of pivots and the depend­
ence of the hinging action on manufacturing tolerance.

(b) A double parallelogram can only collapse to one half of its out­
stretched length in an unconstrained manner. Beyond that, the par­
allelogram bars begin to move in arcs about each other. When attemp­
ting to measure three perpendicular rotations at a human disabled or
deformed joint simultaneously, using this mechanism, only one of
the three potentiometers can be approximately aligned; the other
two will be quite far off axis (8 to 10 cms perhaps). To do the
job of absorbing the resultant off-axis translations, a double­
double parallelogram is needed twice the size of the motions that
must be absorbed. This may result in a bulky and heavy device.
Bulkiness will result in a device getting in the way of walkers, canes, crutches, stair railings, patients' swinging arms, (if the device is at the hip), chairs, etc., that may be present incidentally or as part of a functional test. Also, if the device is too heavy, it will affect the motion patterns that are being measured.

1.3 Scope of this Work

This work is concerned with finding a solution to the problem of measuring the motion pattern of human joints (both lower limbs simultaneously) under dynamic conditions. A clinically viable electrogoniometric solution to this problem is sought in the form of a single module that will work at any and all of the six lower limb joints. Criteria for evaluation of this device have been established, based on a year's clinical experience with an electrogoniometer.

Several alternative solutions are considered and evaluated using these established criteria. The parallelogram chain (picked out of the conceptual design alternatives) is designed in detail, fabricated and dynamically tested on a specially made joint simulator. The device is tested in terms of:

(a) the effect of the accuracy of measurements when the device is located at various positions with respect to the joint simulator;
(b) two different grades of material used in fabricating the chain;
(c) the effect of varying the number of parallelograms used;
(d) the effect of varying the speed of movement of the joint, and how the device is able to follow the true motions from slow walk to slow run.

Conclusions and recommendations for future work are outlined at the end of this thesis.
CHAPTER II

DESIGN CRITERIA
2.1 Design Criteria

Most of the design criteria mentioned in this chapter have been indirectly considered and explained in the discussions of chapter one. Most of the remaining criteria are obvious in their meaning, but for completeness are included. In establishing these criteria, an overall system to measure the motion pattern of the lower limb joints was kept in mind as the central problem. This was done so as the module that will result from the design work will be compatible to use at all lower limb joints in a clinical setting. The criteria will be used to evaluate the problem solutions. The criteria are organized from two points of view - the patient's, and the clinic team's:

(a) Patient:

1. low weight (minimize effect on movement patterns)
2. small size (minimize encumberances with surroundings)
3. minimal constraining forces (minimize effect on movement pattern)
4. good fit and comfortable attachment (adjustable to fit all patients)
5. easily fitted (quickly and easily attached, on and off)
6. good aesthetic affect on patient (feel, look, noise, etc.)
7. good protection from device (pinch-free, etc.)
8. minimal discomfort (pain for example)

(b) Clinic. Team:

1. ability to monitor:

   (i) Hip: flexion-extension
       abduction-adduction
       internal-external rotation
(ii) Knee: flexion-extension
valgus-varus (dealing with abnormality)
internal-external rotation

(iii) Ankle: flexion-extension
inversion-eversion
internal-external rotation

2. ability to monitor hip, knee and ankle of both legs simultaneously

3. good reproducability of data:
   (i) self-aligning or not
   (ii) good fixation of device to the patient
   (iii) minimal constraining forces in action of the device

4. easy to fit to all patients with allowances for varying amounts of deformity

5. minimal use of assessment time for:
   (i) calibration of the device
   (ii) putting the device on and removing it
   (iii) recording the data:
      a. quickly done
      b. easy equipment to operate
      c. accurate data
      d. ability to compare data easily

6. minimal amount of equipment used - direct measurements made
   - minimum number of transducers used

7. minimum cost in manufacture of system and components

8. maximal reliability

9. minimal repair costs
CHAPTER III

PROPOSED SOLUTIONS
3.1 Introduction

The solutions proposed in this chapter to solve the motion measurement problem are presented as conceptual ideas only; they are not detailed, completely workable solutions, but rather, rough proposals presented for the evaluation that follows in chapter five. These proposals are presented in the order they are found in the author's design journal and show the process of synthesis gone through in learning how past devices worked, how they could be improved and how this learning and improving process resulted in new ideas being generated.

By the time the first proposal (next section, 3.2) had been started the literature had been reviewed and six months clinical experience with electrogoniometry had been completed. At this point two decisions were made which shaped the subsequent design work:

(a) A module was wanted that could be attached across any joint of the lower limb (but also looking ahead to the possibilities of the upper limbs and head) to measure at least the three components of rotation that can occur in normal and abnormal joints.

(b) It had been decided to locate all the equipment to the outside or lateral sides of the limbs thus eliminating the problem of attachment of equipment to knock-kneed patients (valgus deformity).

The possibility of attaching to boney landmarks present on the lateral side of a limb also made this last idea attractive. These landmarks are:

1. the crests of the ilia (hip bones)
2. the greater trochanters and lateral epicondyles of the femurs in patients where this is feasible (thigh bones)
3. heads of the fibulae and lateral malleoli (leg bones)
4. Calcanea (where possible) and the heads of the fifth metatarsals (foot bones)

At these points where the bones are subcutaneous (just under the skin) or nearly so, a small amount of medical grade adhesive on small rubber suction cups or rubber V-shaped fingers, with accompanying straps, would give as positive attachment (short of pins into the bone) as electrogoniometry could hope for. The modules could then attach across the joints to adjustable telescoping members, themselves supported at the boney landmarks.

3.2. Single Parallelogram

In the action of Lamoreux's device, besides the parallelogram and the lower hinges that allowed the whole mechanism to shorten or lengthen as the thigh and the leg approached each other, the position of the parallelogram on the limb was important. With the plane of the parallelogram parallel to the limb (in a plane perpendicular to the flexion-extension axis, or in the sagittal plane) and allowing small amounts of hinging out from the limb, only flexion-extension could be measured; there was no parallelogram effect between the supporting cuffs, on the internal-external rotation potentiometer, no self-aligning action. If the plane of the parallelogram was perpendicular to the limb (in a plane perpendicular to the internal-external rotation axis or in the transverse plane) then only internal-external rotation could be measured because there was no parallelogram effect or no way of making the flexion-extension potentiometer self-aligning without a functioning parallelogram between the supporting cuffs. With the parallelogram at some intermediate position, however, both flexion-extension and internal-external rotation could be measured in a self-aligning manner. How would a mechanism function if the
parallelogram in it was mounted skewed to all three perpendicular planes, that is, skewed to the sagittal, coronal and transverse planes and not just the transverse and sagittal planes as was Lamoreux's device?

The schematic drawing of this device is shown in Figure 10. The potentiometer at B is for measuring flexion-extension, at E internal-external rotation and at H abduction-adduction (or valgus-varus). To allow for the proper action of the parallelogram, a universal mount J is needed instead of the simple double hinge of Lamoreux. The parallelogram is shown vertically in the figure but would be tilted out from the page to give the true alignment.

Figure 10. Schematic drawing of the single parallelogram

The addition of the abduction-adduction (varus-valgus) potentiometer introduces a problem into the system. For the proper action of the parallel-
ogram in recording flexion-extension, motion in and out from the limb is necessary in the universal linkage. These motions will cause an error in the abduction-adduction reading. Tentatively, it may be possible to add potentiometers at the axes F and G and suitably add or subtract voltages to obtain the proper abduction-adduction readings. Therefore, this design will have five potentiometers to measure the three movements.

3.3 Double Parallelogram

The double parallelogram will allow unconstrained collapse (within the limits set by link lengths) but will transmit a rotation. If this device were used not as Gordon Judge used it but more as Lamoreux did the single one, the number of potentiometers and hinges required (compared to the previous example) may be reduced. Only one of the few ways this could be done is considered, and a schematic drawing of this way is shown in Figure 11.

![Figure 11. Schematic drawing of the double parallelogram](image)
Again, probably another potentiometer would have to be added at axis F to allow for corrections to be made to the abduction-adduction measurement. This leaves this design requiring four potentiometers to measure three movements.

3.4 Telescoping Unit

A telescoping rod electrogoniometer could be built consisting of a telescoping rod mounted between universally joined ends, one end to the thigh cuff and the other end to a leg cuff (Figure 12). Three potentiometers mounted at each end of the rod would be sufficient to deduce three perpendicular rotations occurring at the joint. For example, take the measurement of flexion-extension. With two potentiometers mounted, one on the thigh cuff and one on

Figure 12. Schematic drawing of the telescopic unit
the leg cuff with the telescoping connecting bar between them, if one knows
the rotation of the bar with the thigh cuff (thigh potentiometer) and in turn
the rotation of the bar with respect to the leg cuff (leg potentiometer) then
one can deduce the rotation of the thigh cuff with respect to the leg cuff,
e.g., add the appropriate angles and subtract from 180°; this could all be
set up by adding and subtracting voltage levels. The other two angles are
analogous. At worst, this data manipulation could be done by a micro pro-
cessor (a small programmable calculator valued at from $300 to $400).

3.5. Parallelogram Chain

The device shown conceptually in Figure 13 will match the actions
of Judge's device minus the hinge and collapsibility problems. This is done by stacking double-double parallelogram boxes on top of each other at right-angles. The corners of the boxes are thinned to allow hinging without free-play. By adding more boxes to this growing chain, theoretically, any amount of collapsibility can be obtained. A small and light weight plastic triple-triple parallelogram chain is depicted in Figure 13. The parallelogram could be a double-double, that is, 2-2, or 3-3, or 4-4, or 2-3, 3-4 etc. A typical plastic hinge is shown at point G. The size and number of parallelograms will be determined by the motion one wishes to absorb.
CHAPTER IV

EVALUATION AND SELECTION
4.1 Evaluation and Selection

Out of the criteria presented in Chapter II, thirteen relevant to the modular linkage design have been selected for evaluation purposes. These are:

(a) weight
(b) size
(c) forces resisting motion
(d) mechanical safety
(e) aesthetics
(f) ability to measure three rotations
(g) applicability to any joint
(h) self aligning
(i) accuracy of results
(j) minimal number of potentiometers
(k) reliability
(l) cost of repair

Looking generally at the four ideas of Chapter III, the single and double parallelogram concepts could be considered essentially the same. The double parallelogram would probably be lighter, be more aesthetically pleasing, have one less potentiometer and would probably be cheaper to make. In comparing the telescoping unit to the double parallelogram, the telescopic unit would probably be safer in operation, aesthetically simpler looking, and cheaper to build. In other areas they are almost equal except that the telescopic unit needs two more potentiometers than the double parallelogram. The parallelogram chain is equal to or better than the other designs when compared using these criteria. The parallelogram chain uses the minimum three
potentiometers, minimizing the complexities of the electrical system. By varying the number of parallelogram units for each chain, the device can be adjusted to optimally perform at any joint, given the variability of motions at different joints; truly, a modular design. The cost of manufacturing is at worst equal to the other designs because the chain can be cast from a plastic, the unit cost dropping as more are made.

The parallelogram chain also compares well with the designs listed in Chapter II. The self-aligning feature makes it clinically more viable than the devices of Karpovich and Johnston. The chain will give an extra set of angular information at a joint as compared to Lamoreux's device, with the use of one small mechanism. The parallelogram chain does not need a computer to give clinically useful results as does Kinzel and Hillberry's space mechanism. Compared to Judge's design, the chain will reduce the hinging and collapsibility problems associated with the double-double parallelogram.

Following from these many subjective arguments, the parallelogram chain was chosen for detailed design, fabrication and testing with the thought that an improvement in techniques of electrogoniometry and patient assessment could be effected.
CHAPTER V

DETAILS OF DESIGN
5.1 Introduction

The detailed design that follows is limited to the plastic parallelogram chain shown positioned between the potentiometers of Figure 13. The exploration of alternative methods of attaching the potentiometers (and in turn, the parallelogram chain) to the patient is left for future work. The selection of the working material and the manufacturing techniques used for fabricating the first prototype are discussed in 5.2 and Appendix III and serve to clarify parts of the discussion of 5.3, hinge design.

5.2 Material Selection

The material finally selected for prototype fabrication and testing was the family of polyurethane elastomers. Out of the many other plastics considered, polypropylene is very representative with some to the best material properties. Very tough and fatigue resistant, polypropylene is used in many commercial applications. However, to make the parallelogram chain out of polypropylene, injection moulding is mandatory. The moulds used for this need to be made by skilled people and require a large injection moulding machine for making the part. The expense involved in experimenting with different hinge thicknesses and geometric configurations makes polypropylene unsuitable for the initial prototypes. It may make sense to use polypropylene to obtain optimum properties once the design has been finalized.

The polyurethane elastomers are not ideal for experimentation, but have these advantages:

(a) Polyurethanes can be easily handled. They are commercially available in a two component kit, resin and hardener, and can be mixed and easily poured into and removed from unpressurized moulds.
(b) Since polyurethane can be poured unpressurized, the moulds are relatively less expensive to make. Therefore, more experimental trials can be done in comparison to polypropylene for the same expenditure of time and money.

(c) Polyurethanes are available in hardnesses from that of a soft rubber to hardnesses of structural plastics such as vinyls, polypropylenes and some epoxies. So the scope for experimentation using a single hinge configuration, for example, in a wide range of available material properties is possible.

(d) The polyurethanes are wear and fatigue resistant (rubber-like) and tough in thin sections.

(e) Being able to cast polyurethanes as a liquid will allow design possibilities such as:

1. including various plastic or cloth-like fibers or straps in the hinge (thinned) sections of the mould to take advantage of composite material properties, e.g. strength and unidirectional flexibility at the hinges.

2. inclusion of metal stiffeners in wall sections.

Refer to Appendix III for the casting techniques used with the polyurethane. Refer to Appendix IV for manufacturer's data on polyurethanes.

5.3 Hinge Design

Conceptually, the parallelogram chain uses the thin section flexibility of the material of which it is made to allow the necessary parallelogram scissoring action. To turn this concept into reality, a few variables must be considered:
(a) hinge thickness
(b) hinge geometry

1. at the necked section
2. surrounding the necked section

When considering the forces that are needed to cause scissoring of the parallelograms (the higher the forces, the more error because the forces are transmitted back to the subject tending to change the subject’s motion pattern) it becomes evident that the variables under consideration are dependent upon each other. This implies that a trial and error iteration process be undertaken to arrive at a workable pattern configuration. Because of the expense of having accurate patterns milled and a large volume of work being done in the University machine shop, only two patterns became a reality. The third one is on paper, but will not be machined until after this work is completed.

Basically, two hinge thicknesses and two hinge geometries, one necked down using sharp corners and one necked down using rounded corners, were tried. The two patterns which were made used an asymmetrical hinge while the one still to be done (see Chapter VIII) uses a symmetrical hinge geometry.

(a) Hinge Thickness: Figure 14 shows the drawing of the first pattern made in the machine shop. This design was a result of discussions with the machinist on what materials and techniques were available to him. This was after attempts to make a wood-paper pattern were unsuccessful. Discussions with a professional wood pattern maker about making a completely wooden pattern showed this approach to be impractical.

The minimum hinge thickness of the first pattern was 0.254 mm or 0.010 inches, an estimated minimum value arrived at by examining thin films of polyurethane obtained from flash around mouldings (material over-flowed or squeezed out of mould cavities). This first pattern was made starting first
with a rectangular frame made of 0.010 inch thickness brass plate (shim stock). The rectangle, formed by bending the plate was closed by soldering the ends together in a small lap joint. The brass thick wall sections, (shaded area in Figure 11) were then soldered in the appropriate places to leave small 0.010 inch thick hinges in the corners. The dimensions of the hinge sections ended up being 0.794 mm x 0.254 mm x 19.05 mm or 1/32" x 0.010" x 0.75".

A shore A 70 polyurethane chain was cast in four trial moulds. The hinges of the chains were failures. The polyurethane formed beads along the hinge sections in two moulds, producing hinges that fell apart when the moulds were handled for casting removal. The castings that survived mould removal failed after they had undergone a few flexes. At this point the hinge sections of the pattern were filletted to obtain a 1.6 mm or 1/16" radius with fiber-glas putty. This also increased the hinge thickness to about 0.75 mm or 0.030".

![Figure 14. First parallelogram chain prototype pattern](image-url)
Again, a Shore A 70 polyurethane was cast in four trial moulds but this time all the castings were good. These hinges were not too stiff, but it could be envisioned that harder polyurethanes at this hinge thickness would take larger forces to cause the parallelograms to scissor, and this force had to be minimized. It was estimated then that the boundaries upon hinge thickness varied from 0.254 mm to 0.75 mm or from 0.010" to 0.030".

The final hinge thickness tried was that of 0.504 mm or 0.020" on a new, accurately milled pattern. Materials of Shore A 75, 90 and D 60 were cast. All the hinges held together and were easy to flex. Hand testing indicated they were fatigue resistant. (It is beyond the scope of this work to do detailed fatigue and force testing.) These castings were adequate for the subsequent testing imposed on them.

(b) Hinge Geometry: Of the hinges of 0.254 mm thickness, one side of the hinge was part of a 90° corner, the other part of a 135° corner. The stress raiser effect of the 90° corners plus any entrapped bubbles (resultant beading effect) may have been the reason why the hinges that did survive mould removal failed after a few pulls and flexes. The 1.6 mm radius on the 0.75 mm thick hinge may have reduced this stress situation, but hinge strength was simultaneously increased. With these tentative thoughts in mind, the geometry of the accurately milled pattern (0.504 mm hinge thickness) was explored. (The first brass pattern was discarded at this point due to discrepancies in the lengths of the sides causing non-parallelogram action.) Figure 15 shows the various hinge geometries considered at this time. Figure 15 (4) was chosen being close to the shape originally tested and the drawing, Figure 16, resulted. Since the sharp corners would have to be hand filed, a time consuming and less accurate process than using the milling machine, a 1.59 mm radius (1/16" radius)
milling cutter (smallest that could be used accurately) was used to cut the hinges in the pattern. This resulted in a hinge geometry as per Figure 15 (1). This hinge geometry is discussed again in Chapter VIII after some test results have been presented.

Figure 16. Second parallelogram chain pattern

Figure 15. Some hinge geometries
CHAPTER VI

TEST APPARATUS
6.1 Test Apparatus

The parallelogram chain was tested in terms of its ability to monitor three perpendicular rotations simultaneously or individually under various standard conditions. A joint simulator (Figure 17) was built to test how well the potentiometers on the parallelogram chain could track the potentiometers on the mechanical hinges of a simulated human joint.

In Figure 17, the mechanical hinges and corresponding potentiometers are
A - flexion-extension
B - valgus-varus or abduction-adduction, and
C - internal-external rotation

The corresponding potentiometers on the parallelogram chain are D, E and F respectively. The adjustable connectors attached to rod G (the thigh) and to rod H (the "lower leg") allow the parallelogram chain to be positioned relative to the mechanical hinges. The "thigh" rod G is driven around in an elliptical pattern by the chain and motor shown in the top of Figure 17. The "lower leg" rod H is mounted rigidly to the base of the simulator. Three perpendicular rotations are imparted simultaneously to the simulator in each
elliptical cycle.

The motion pattern through which the "thigh" rod travels with respect to the "lower leg" rod is approximately that of a badly functioning, walking human arthritic knee joint; that is, $0^\circ$ to $85^\circ$ of flexion, $0^\circ$ to $25^\circ$ of varus and/or (in the simulator's case, and) valgus, and $0^\circ$ to $20^\circ$ of internal or external rotation. By varying the voltage to the small gear reduced D.C. motor, the speed of the motion can be changed.

A power supply and signal attenuator box was built to energize the potentiometers and to reduce the signal power from the potentiometers to be compatible with the galvanometers of the ultra-violet light strip chart recorder. Consideration in the design of the attenuator box was given to drawing minimal current from the potentiometers so that their linearity was maintained. A circuit diagram for the attenuator/power supply box, the derivation of a formula relating the current drawn from the potentiometers and the other circuit parameters to the linearity of the potentiometer output are all shown in Appendix V.

The potentiometers were mounted in series, perpendicular to one another. Care was taken in mounting the potentiometers not to allow any twisting moments about the potentiometer shafts to develop as the chain was compressed or extended during testing. These unwanted moments would cause errors in the measurements. Various configurations of the potentiometers were tried; two on top, one on the bottom; two on the bottom, one on top; the final configuration worked the best, with all potentiometers connected in series, each connected to the shaft of the one before it, mutually perpendicular, all mounted ontop of the chain. (This can be seen at the top of Figure 20.)
The strip chart recorder used focused beams of ultra-violet light position controlled by small mirrors on the galvanometers. The light exposes the photographically sensitive emulsion on the strip chart paper. One useful feature of this recorder was that the light beams could cross, and it was possible to superimpose them. This allowed the recording of the magnitude and position, in the joint simulator's motion cycle, of errors occurring between the parallelogram chain and the mechanical joint.

6.2 Test Procedure

Figure 18 shows the coordinate system used to locate the centre of the top and bottom of the parallelogram chain with respect to the mechanical joint (+x is out of the photograph). With various (differing sizes and materials) parallelogram chains located in different positions with respect to this coordinate system, up to four runs were made:

![Joint simulator coordinate system](image-url)
(1) The starting position for all these tests was with the flexion-extension potentiometer of the parallelogram chain aligned with the flexion-extension potentiometer of the mechanical joint. This made the coordinates of the top of the parallelogram chain, $x = +8.5\;\text{cms}$

$y = -1.5\;\text{cms}$

$z = -6.0\;\text{cms}$

The bottom of the chain was in the same $x,y$ position with the $z$ position adjusted so that the chain would function in any of the extreme positions of the test cycle, a position that was judged to be not collapsing or extending beyond the limits of movement of the parallelogram chain. Figures 19 and 20 show the chain in a typical fully extended or collapsed position.

Figure 19. The parallelogram chain in a fully extended position

Figure 20. The parallelogram chain in a fully collapsed position
The chain was positioned (top at $z = -6.0$ cms) as far in the positive $y$ direction as possible. The top $y$ and the bottom $y$ and $z$ positions were adjusted (top $y = \text{bottom } y$) to give free action of the chain and to allow the chain to clear the mechanical joint in extreme positions of the motion cycle.

The chain was positioned in the maximum $x$ position possible with the top at $z = -6.0$ cms, $y = -1.5$ cms. The $x$ position of the top and the $x$ and $z$ positions of the bottom ($x\text{'s equal}$) were adjusted to give free action to the chain.

The chain was positioned in the maximum $z$ position possible with top and bottom at $y = -1.5$ cms. The $x$ and $z$ positions of the top and bottom ($x\text{'s equal}$) were adjusted to allow free action of the chain.

Four runs were done with a 4-4 chain of the Shore D 45 or 6403 elastomer. Two runs each of the 4-4 and 3-3 chains, of Shore D 60 or 6404 elastomer were done.

Before the runs were started, all six potentiometers were calibrated using a dial clamped to the potentiometer shafts. The dial had 100 divisions and was readable to the nearest 0.2 of one division. The trace on the strip chart recorder was readable to within $^{\pm} 0.5$ mm or with the calibration set at $25^\circ$/cm, about $^{\pm} 1$ degree. The calibration curve (all virtually the same) for a typical potentiometer is shown in Figure 21. (Six Bourns precision potentiometers were used: 10 turns, 10 K ohm resistance, 0.2% independent linearity.)

All runs were done at two speeds. These were determined by the input voltage to the driving motor, 5 and 10 volts. Five volts turned out to
Figure 21: Typical potentiometer calibration curve.
be a moderate to slow walking speed, and 10 volts was comparable to slow running. This conclusion was arrived at by comparison of Lamoreux's results to the results of this work in terms of maximum angular velocity recorded, a direct indicator of walking speed. This was obtained by calculating the maximum slopes occurring in the angle vs. time curves of both sets of results. For Lamoreux's study the maximum angular velocity for a subject on the verge of running was 420°/sec. In this study, (as seen in the next section, and in Figure 38) the maximum angular velocity calculated from the data at the 10 volt speed was 460°/sec.

6.3 Results

6.3.1 Data

Figures 22, 24, 26, 28 show runs 1, 2, 3, and 4 on the parallelogram chains made of Shore D 45 elastomer using 4-4 parallelogram units. These runs were done at a motor voltage of 5 volts, comparable to moderate or slow walking. Figures 23, 25, 27, 29 are the same as 22, 24, 26, 28 respectively except that the motor voltage was 10 volts, comparable to slow running. The left hand curves on each of these figures are pairs of recordings from the joint simulator and the parallelogram chain for each of the three mutually perpendicular rotations. These curves are graphs of (vertically or up/down the page) angular change vs. time. On the right hand side of the figures, the pairs of curves are superimposed to show the errors occurring between the records. Figures 30 and 32 were of a 4-4 parallelogram chain, runs numbered 1 and 4, made of a Shore D 60 elastomer with the motor at 5 volts. Figures 31 and 33 are the same as 30 and 32 respectively except that the motor voltage was 10 volts. The last set of figures 34, 36 (at 5 volts) and 35, 37
(at 10 volts) were for a Shore D 45 elastomer used in a 3-3 parallelogram chain. The letter code for these figures is shown below:

(a) Flexion-extension, joint simulator
(b) Flexion-extension, parallelogram chain
(c) a and b superimposed
(d) Valgus-varus, joint simulator
(e) Valgus-varus, parallelogram chain
(f) d and e superimposed
(g) Internal-external rotation, joint simulator
(h) Internal-external rotation, parallelogram chain
(i) g and h superimposed

One centimeter vertically = 25°
One centimeter horizontally = 1.2 seconds

The maximum (worst case) value for the measured errors from these runs is shown in Table I. These values were obtained by direct measurement for the corresponding run records. The section in each run where the tracings were superimposed was used to establish the angular errors listed in Table I. The first digit of the run numbers (top of Table I) refers to:

(1) 4-4 chain of Shore D 45 elastomer
(2) 4-4 chain of Shore D 60 elastomer
(3) 3-3 chain of Shore D 45 elastomer

The second digit of the run number refers to the test positions listed in section 6.2, Test Procedure. For example, Run 3.1 was done in the starting or (1) position with the 3-3 chain of Shore D 45 elastomer. Therefore runs 1.1, 2.1 and 3.1 were tests on different materials and chain sizes done in comparable positions.
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Figure 22: 4-4 Parallelogram Chain, Run 1.1

Top: \( x = +8.5 \) cm \( y = -1.5 \) \( z = -6.0 \)
Bottom: \( x = +8.5 \) cm \( y = -1.5 \) \( z = -21.5 \)

Material: Shore D45 (#6403)
Motor: 5 volts
Figure 23: 4-4 Parallelogram Chain, Run 1.1

Top: \( x = +8.5 \text{ cm} \)  
\( y = -1.5 \)  
\( z = -6.0 \)

Bottom: \( x = +8.5 \text{ cm} \)  
\( y = -1.5 \)  
\( z = -21.5 \)

Material: Shore D45 (#6403)
Motor: 10 volts
Figure 24: 4-4 Parallelogram Chain, Run 1.2

Top: $x = +9.5$ cm  Bottom: $x = +9.5$ cm
$y = +5.0$  $y = +3.0$
$z = -6.0$  $z = -18.5$

Material: Shore D45 (#6403)
Motor: 5 volts
LEAF 46(d) OMITTED IN PAGE NUMBERING.
Figure 25: 4-4 Parallelogram Chain, Run 1.2

Top: \(x = +9.5 \text{ cm}\)  
Bottom: \(x = +9.5 \text{ cm}\)

\(y = +3.0\)  
\(y = +3.0\)

\(z = -6.0\)  
\(z = -18.5\)

Material: Shore D45 (#6403)
Motor: 10 volts
Figure 26: 4-4 Parallelogram Chain, Run 1.3

Top: \( x = +10.5 \text{ cm} \)  
Bottom: \( x = +10.5 \text{ cm} \)  
\( y = -1.5 \)  
\( z = -6.0 \)  
\( y = -1.5 \)  
\( z = -21.5 \)  

Material: Shore D45 (#6403)  
Motor: 5 volts
Figure 27: 4-4 Parallelogram Chain, Run 1.3

Top: $x = +10.5$ cm  Bottom: $x = +10.5$ cm  
$y = -1.5$  
$z = -6.0$  

Material: Shore D45 (#6403)  
Motor: 10 volts
Figure 28: 4-4 Parallelogram Chain, Run 1.4

Top: \(x = +8.5\text{ cm}\) \(y = -1.5\) \(z = -1.5\)

Bottom: \(x = +8.5\text{ cm}\) \(y = -1.5\) \(z = -18.5\)

Material: Shore D45 (#6403)
Motor: 5 volts
Figure 29: 4-4 Parallelogram Chain, Run 1.4

Top: $x = +8.5$ cm  
Bottom: $x = +8.5$ cm  
$y = -1.5$  
$z = -18.5$

Material: Shore D45 (#6403)  
Motor: 10 volts
Figure 30: 4-4 Parallelogram Chain, Run 2.1

Top: $x = +8.5$ cm  Bottom: $x = +8.5$ cm
$y = -1.5$  $y = -1.5$
$z = -6.0$  $z = -21.5$

Material: Shore D 60 (#6404)
Motor: 5 volts
Figure 31: 4-4 Parallelogram Chain, Run 2.1

Top: $x = +8.5$ cm  
Bottom: $x = +8.5$ cm  
$y = -1.5$  
$z = -6.0$  

Material: Shore D60 (#6404)  
Motor: 10 volts
Figure 32: 4-4 Parallelogram Chain, Run 2.4

Top: $x = +8.5$ cm  
$y = -1.5$  
$z = -1.5$

Bottom: $x = +8.5$ cm  
$y = -1.5$  
$z = -18.5$

Material: Shore D60 (#6404)
Motor: 5 volts
Figure 33: 4-4 Parallelogram Chain, Run 2.4

Top: $x = +8.5$ cm  
$y = -1.5$  
$z = -1.5$

Bottom: $x = +8.5$ cm  
$y = -1.5$  
$z = -18.5$

Material: Shore D60 (#6404)
Motor: 10 Volts
Figure 34: 3-3 Parallelogram Chain, Run 3.1

Top: \( x = +8.0 \text{ cm} \) \quad Bottom: \( x = +8.0 \text{ cm} \)
\( y = -1.5 \) \quad \( y = -1.5 \)
\( z = -6.0 \) \quad \( z = -19.0 \)

Material: Shore D45 (#6403)
Motor: 5 volts
Figure 35: 3-3 Parallelogram Chain, Run 3.1

Top: \( x = +8.0 \text{ cm} \)
\( y = -1.5 \)
\( z = -6.0 \)

Bottom: \( x = +8.0 \text{ cm} \)
\( y = -1.5 \)
\( z = -19.0 \)

Material: Shore D45 (#6403)
Motor: 10 volts
Figure 36: 3-3 Parallelogram Chain, Run 3.4

Top: $x = +8.5$ cm  Bottom: $x = +8.5$ cm
$y = -1.5$  $y = -1.5$
$z = -3.5$  $z = -17.2$

Material: Shore D45 (#6403)
Motor: 5 volts
Figure 37: 3-3 Parallelogram Chain, Run 3.4

Top: $x = +8.5 \text{ cm}$, $y = -1.5$, $z = -3.5$

Bottom: $x = +8.5 \text{ cm}$, $y = -1.5$, $z = -17.2$

Material: Shore D45 (#6403)
Motor: 10 volts
The three angular measurements made at 5 volts and 10 volts are listed on the left hand side of Table 1. In the 10 volt runs transient effects began to show up. It must be noted that in getting the angular velocity of 465°/sec., comparable to slow running, an abrupt reversal of angular velocities (+465°/sec. to -465°/sec.) occurs, much more severe than would occur in human motion. A comparison of a +420°/sec. to a -420°/sec. reversal in a subject on the verge of running (from Lamoreux's work) compared to the +460°/sec. to -460°/sec. reversal occurring on the joint simulator is seen in Figure 38. The conclusion to be drawn from this is that the transient impacts are too severe a test and will not be encountered in practice, so can be ignored.

What should be emphasized is the ability of the parallelogram chain to initially follow the high angular velocity and to subsequently measure the appropriate angular change after the transient has died away, that is, give the appropriate steady state response. A comparison of the steady state responses (at 10 volts) is shown in Table 1. The ability of the parallelogram chain to follow the initial high angular velocity inputs can be seen in the valgus-varus runs done at 10 volts or slow running.

The transient effects shown in Figure 38 occur in all the 10 volt records at the same time in the motion cycle. The records shown in Figures 22 to 37 are arranged so that a vertical line (top to bottom of the figure) through the curves intersects the curves at the same time in the cycle. Using Figure 38 as a guide, the appropriate sections of the curves, which can be ignored due to transient effects, can be located. The sections of Figure 27 that are circled denote some examples of transient responses.
Figure 38. The abrupt reversal of angular velocities obtained with the author's mechanical joint simulator on the left as compared to the smooth reversal of angular velocities obtained from Lamoreux's record, on the right, of a normal subject walking.

6.3.2 Discussion

With the exception of runs 1.1, 2.1 and 3.1 (runs done in the starting position with flexion-extension potentiometers aligned), all runs were done at the extreme limit of the parallelogram free action (see section 6.2 for explanation). Once the parallelogram chain is taken beyond the limits of free compressibility and extensibility, the error between the simulator joint motion and the joint motion measured by the parallelogram chain increases dramatically. (These curves are not presented as they show extremely poor, and in some cases, non-existant motion correlation). Using the parallelogram location data found at the bottom of each figure, (figures 22, 23, 30, 31, 34, 35 excepted) a volume within which the chain functions
with relatively low error can be established for the two different lengths of parallelogram chain tested; the 4-4 parallelogram chain unit had an extended length of about 15.5 cms and the 3-3 chain had a length of 13.0 cms. For the 4-4 chain the volume was bounded by the coordinates:

\[
\begin{align*}
y &= 3.0 \text{ to } -6.0 \text{ cms} \\
x &= 8.5 \text{ to } 10.5 \text{ cms*} \\
z &= -1.5 \text{ to } -10.5 \text{ cms.}
\end{align*}
\]

* N.B. The minimum x value is limited by the size of the joint simulator. +8.5 cms is as close to the mechanism as the chain could be put.

This gives effectively a working rectangular volume of 9 cms by 9 cms by 2 cms, the 2 cms partly limited by the test mechanism. This working volume is dependent upon the amounts of off-axis translations that have to be absorbed. If, for example, the joint simulator were set to approximate the motion of a normal knee (and not a severely disabled one as it was), the working volume could have been increased approximately 5 cms in each direction to a volume of 14 x 14 x 7 cms. For the 3-3 chain the volume was bounded by the coordinates:

\[
\begin{align*}
x &= +8.0 \text{ to } +9.0 \text{ cms*} \\
y &= +1.0 \text{ to } -4.0 \text{ cms} \\
z &= -3.5 \text{ to } -8.5 \text{ cms}
\end{align*}
\]

* N.B. The +8.0 cms was limited by the width of the joint simulator.

This gives effectively a working rectangular volume of 5 x 5 x 1 cms, the 1 cm partly limited by the joint simulator. This volume will also increase with reduction in motion of a joint.
The concept of a working volume is directly applicable to patient joint motion monitoring. The larger the working volume, the less care and time is necessary for positioning the parallelogram chain (and its mounting frame, etc.) on the patient's limb. With non-self-aligning electrogoniometers much time is taken to align the potentiometers with the axis of rotation of a joint. This has to be done carefully to (a) get accurate results, (b) and get reproducability of results (e.g. comparing records of a patient at two different trials). Take, for example, the 4-4 chain; It may function if:

(a) the potentiometer cluster at the top of the chain is anywhere within 4.5 cms (1.77 inches) forward or backward of the axis of flexion-extension and  
(b) the potentiometer cluster is anywhere within 4.5 cms. up or down from the flexion-extension axis and  
(c) the chain is not more than 10.5 cms. (4.14 inches) from the centerline of the limb, front view.

Then any recording made will give low error, reproducible results. The self-aligning feature coupled with a suitable working volume will substantially reduce patient fitting time and subsequently greatly reduce overall monitoring time. This will allow more patients to be monitored and assessed than is currently possible with any existing device.

In most cases the shapes of the corresponding curves on each figure (22 to 37) are similar. With the two traces separated (left hand side of each figure) the curves follow each others bumps and shifts. The superimposed curves show (right hand side of each figure) that while the shape may be maintained, the magnitude of the output was reduced. The chain had absorbed
some of the motion. It is these errors that have been measured from the recordings and listed in Table 1. Although there are errors in angle magnitude, the fact that shape is roughly maintained would point to the correctness of the parallelogram chain concept and point to a change of material or material properties and/or hinge redesign to correct for the errors in magnitude of the output.

There is a discrepancy between the pair of internal-external rotation records partly due to the joint simulator. The problem with the joint simulator is that the potentiometers measuring flexion-extension and valgus-varus (on the simulator) are mounted, fixed relative to the leg rod, H, of Figure 17, while the potentiometer measuring internal-external rotation (on the simulator) is mounted on the thigh rod G. When a motion is imparted to the flexion-extension or valgus-varus potentiometers, a motion is measured relative to the lower leg fixed reference frame. When a motion is imparted to the external-internal rotation potentiometer, a motion is measured relative to the thigh rod which moves relative to the lower leg fixed reference frame. This causes measurement discrepancies because all the potentiometers on the parallelogram chain are measuring relative to the lower leg. When the thigh rod G and the lower leg rod H are in line (at 180°, full extension) then and only then can a true internal-external rotation on the joint simulator be measured. In the test results (Figures 22 to 37) the major (up going) peak on the internal-external rotation records is occurring at full extension (by design). The measurement from the joint simulator is only a standard of comparison at full extension and no other position in the motion cycle. The downward drop in some of the internal-external rotation measurement curves taken from the parallelogram chain may be fairly accur-
ate but at this position in the motion cycle there is no true motion measurement to compare with. The errors reported in Table 1 for internal-external rotation, are only from the major (up going) peaks on the records.

To test the effect of changing material properties on the results, runs numbered 1.x and 2.x were done. The only difference between the runs (for corresponding speeds and positions) was that runs 2.x had a parallelogram chain made of a Shore D 60 rubber and runs 1.x had a chain made of Shore D 45 rubber, the D 60 having approximately twice the hardness of the D 45 (as the manufacturer says). These tests showed an increase in error with the harder material. The results show a reduction in measured error of one test, no change in another test and an increase in error in the remaining four tests. This average decrease in function may be due to inferior thin section material properties at the higher hardness, eg. some translation of each hinge's centre of rotation may be forced to occur because of a decrease in material flexibility. The D 60 rubber was observed not to stand up to repeated flexing as well as the D 45 rubber. A thin white line began to appear in the hinges of the D 60 as testing progressed. (The D 45 did not show this.) This would indicate the material had gone beyond its elastic limit and failure was near (some did fail).

The effect of the hinges (hinge geometry) on the measured errors can be seen in a comparison of runs numbered 1.x and 3.x where the only difference between the two sets of runs (for corresponding speeds and positions) was that for run 1.x, a 4-4 chain with 32 hinges was used and for run 3.x, a 3-3 chain with 24 hinges was used. These tests showed less error with the smaller number of hinges. The flexion-extension results of runs 1.1 and 3.1 were the only exception to this, showing an increase in error while all five
other tests showed a reduction in error. This would indicate that the hinge design could be improved. (See Recommendation For Future Work, 1, page 56.)

In comparing the results obtained at a 5 volt motor voltage (slow walking) and a 10 volt motor voltage (slow running) approximately the same errors occur. Again, the shapes of the curves are maintained (between the simulator and the chain) but the magnitudes are diminished by the parallelogram chain absorbing some of the angular change. It could be concluded then, that the parallelogram chain was able to follow the dynamic motions of simulated slow running.
CHAPTER VII

SUMMARY AND CONCLUSIONS
7.1 Summary and Conclusions

1. (a) There is a need for a device to measure motions of a disabled person's joint or many joints simultaneously under dynamic conditions, for (a) determining the patient's functional status and (b) assessing the effects of medical treatment. The parallelogram chain will meet this need.

(b) There is a need for a motion measuring device that will measure joint function in the clinic, as the patient is seen by the clinic team. This device must be quickly and easily fitted and give instant, accurate results. The parallelogram chain will meet this need.

2. Because of (1) above, the criteria established for evaluation of motion measuring devices were patient and clinic oriented first and research oriented second.

3. The parallelogram chain design is modular and applicable to any large joint of the upper or lower limbs.

4. The original design generated in this work, the parallelogram chain, in concept has these advantages over other devices:

(a) Accurate and time consuming alignment with joint axes of rotation is not necessary with the self-aligning feature of the parallelogram chain.

(b) Complete angular rotational information will be available at any large joint.

(c) Simple, direct, instant results are available at any large joint.

(d) Reproduceability of results is maximized by the parallelogram chain's self-aligning feature.

5. The hinges of the parallelogram chain are cast integral to the mechanism. This reduces production cost as the number of chains produced increases.
6. (a) The parallelogram chain was tested on a mechanical joint simulator. All previous electrogoniometric work either assumed perfectly operating mechanisms or used a computer to simulate the action of the mechanism. The advantage of the joint simulator is that it can double as a tester to quality control the parallelogram chain castings.

(b) Because the parallelogram chain absorbs off-axis translations the potentiometer motion transducers can be mounted as a cluster atop the chain. This helps minimize the size of the chain-potentiometers combination.

7. (a) The test results show that the parallelogram chain is a sound, workable concept.

(b) The parallelogram chain will follow and measure the dynamic motions of at least slow running.

(c) The 4-4 parallelogram chain has a working volume of 9 x 9 x 2 cm and the 3-3 chain, 5 x 5 x 1 cm, within which low error results can be reproduceably obtained.

(d) The best results obtained from the parallelogram chain (which are comparable or better than those obtained by other workers) occur when the flexion-extension rotational axis of the chain is closely aligned (near) with the flexion-extension axis of the joint while the other two rotational axes are not specifically aligned.

(e) Errors introduced into the results by the joint simulator can be explained and this will allow a new joint simulator (future work) to be constructed.

(f) The test results point out that the main source of error was the hinge geometry of the chain and not the material property variations.
CHAPTER VIII

RECOMMENDATIONS
8.1 Recommendations For Future Work

1. Redesign of the plastic hinge of the parallelogram chain is necessary. Figure 39 shows what happens to the hinge design of Figure 15, (1), under load. This buckling will shift the centre of rotation of the hinge imparting a small error into the action of each parallelogram. The smaller the number of hinges in the parallelogram chain, the smaller the overall error of the functioning chain. This was observed with the test results of the 32 hinge 4-4 chain and the 24 hinge, 3-3 chain. Figure 40 shows the cross-section of an improved hinge design that gives good support to the necked section of the hinge. Figure 49 of Appendix VI shows how this hinge geometry could be incorporated into a new chain design.

2. A light frame that can easily and quickly be fitted to a wide range of patients must be designed and tested.

3. A device to remove potentiometer data from the moving patient must be designed and tested.

4. A fatigue failure analysis should be done on the hinge to determine

![Figure 39: Buckling of the parallelogram chain hinge under load.](image-url)
the life of the polyurethane elastomer and other suitable materials.

5. The joint simulator should be rebuilt to:
   (a) make testing easier,
   (b) eliminate errors due to the placement of the internal-external rotation potentiometer,
   (c) test larger parallelogram chains.

6. It may be necessary to redo tests varying the material properties of the chain to determine the effects on measurement error, once the redesigned chain has been built.

7. Once the size and properties of the parallelogram chain are finalized an investigation into cost and availability of injection moulded polypropylene parts should be done.
REFERENCES


APPENDIX I - Definition of Terms

valgus (abduction)
APPENDIX II - Typical Electrogoniometer Records

Only level walking and flexion-extension of the knee and ankle are presented here for illustrative purposes.

Figure 41 shows the curves obtained for a normal subject, level walking. The two curves can be thought of as graphs; the vertical axis, degrees (angular change of the joint), the horizontal axis, time. The three vertical lines through the figure delineate the points in time when heel strike occurred. Looking at the knee curve first: At heel strike, 1, the leg is fully extended. As the leg moves into stance phase of the walking cycle the knee flexes to a maximum of about 20 degrees, 2. Then the knee extends almost to maximum and again flexes slightly as toe off (stance phase contralateral leg) occurs at 3. Now in swing phase the knee flexes to a maximum of about 65 degrees, 4, and again extends back to zero degrees at heel strike, 5. Looking at the ankle curve: At heel strike, 1, the ankle is in a neutral position and plantarflexes (toes down) to a flat foot at 2. As we move through stance phase and approach toe off at 3 the ankle dorsiflexes (toes up) through a range of about 25 degrees, 2 to 3. After toe off the foot moves...
through swing phase parallel to the floor plantarflexing to point 4 where the foot dorsiflexes in preparation for heel strike at 5.

What information can we get from these records? By running the equipment continuously from start to end of the walk and knowing the distance per lap (350 meters walked in 25 meter laps) we can get:

1. Cadence (steps per minute).
2. Stride length.
3. Variations in: Cadence and stride length. This indicates endurance or fatigue.
4. Knee range of motion used in walking: eg. stance phase $20^\circ$
   eg. swing phase $65^\circ$
5. Ankle range of motion used in walking: eg. range $25^\circ$
6. Impacts or restrictions in motion:
   - where in the walking cycle they are occurring
   - magnitude of motion
7. Shakiness or oscillations.
8. Comparisons between:
   (a) patient's curve and normal subjects curve,
   (b) same patient before and after procedures: eg. surgery therapy, bracing, etc.
9. Direction and amount of instability.
10. etc.

Figure 42 shows the walking curves obtained from an arthritic patient, superimposed upon the normal curves shown in Figure 41. This is a record of a 53 year old woman with a fifteen year history of progressively worsening rheumatoid arthritis in both knees. She has a McIntosh arthro-
plasty (joint replacement) in her right knee and the left knee, the one tested, has had a synovectomy (surgical procedure) in 1968 and a McIntosh arthroplasty in 1971. The left knee caught painfully occasionally.

The records (black lines in figure 42) are noticeably abnormal, especially the knee record. In stance phase, 1, the knee does not flex at all; normal stance phase flexion is 20°. In swing phase, 2, she only flexes 35°, half that of a normal person. Her comfortable cadence decreased throughout the test and she was only able to complete 100 meters. Although she could only walk the 100 meters the patterns were steady with little or no shakiness. However in subsequent testing, stairs especially, marked amount of shakiness was noted (the average value of the amplitude of the oscillations
can be measured). Because the knee channel was not completely tuned the
day of the test (the ankle record was good however) noise or artifact ob-
escured the effect of the painful clicking in the knee observed by the
patient but this was reflected in the ankle pattern at point 1. This clicking
occurring every six or seven steps is located at 35% into the walking
cycle, that is, in stance phase just as the leg is to become totally
body weight bearing.

Figure 43 shows the walking curves obtained from another patient.
The knee record is significant here. It was noted that at heel contact the
knee was not going into a normal pattern of extension. The initial section
of the curve is displaced upward as can be seen by comparing it with the
lighter shaded line representing her "normal pattern".

The crucial thing was that there is a leg length discrepancy.
When the shoe was adjusted to bring the limbs closer to equal length, the
curve obtained was shifted close to the normal shape.
APPENDIX III - Casting Techniques

A flow chart of the process used in casting the parallelogram chain is shown in figure 44. The pattern, A, of the parallelogram chain is enclosed in a wooden frame, B, and has RTV (Room Temperature Vulcanizing) mould making rubber mix F, poured around it. After a 24 hour cure the wooded frame is stripped from the mould and after the pattern is removed a mould is left, C, into which can be poured the polyurethane mix, G. Before either the RTV or the polyurethane is poured they need the bubbles entrapped by mixing removed in a vacuum chamber, E. The casting, D, is removed.

Figure 44: The casting process
from the mould before or after oven curing depending upon the strength of
the uncured casting. As a rule of thumb the castings poured from the
polyurethanes of hardness Shore A90 or less can be removed after one or
two days room temperature air cure. The Shore D50 and above polyurethanes
don't have the initial strength in thin section to resist the forces on the
casting as it is removed from the mould. According to the manufacturers
data sheet and personal experience most of the physical properties of the
material can be obtained in seven days room temperature air cure of some­
what better properties with cure at $82^\circ C$ ($180^\circ F$) for 16 hours.

The vacuum chamber, E, of figure 44 was constructed of a 12 inch
length of 8 inch O.D., 0.25 inch wall circular steel pipe. A wooden base
was set in place with a fiberglass resin. The top was a 0.5 inch thick
piece of plexiglass with a gas fitting for air removal threaded in place.
A small vacuum pump was used to evacuate the chamber to about -28.0 inches
Hg gauge.
Appendix IV: Summary of manufacturers data sheet of the Polyurethane elastomers.

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<td>390/400</td>
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<td>3400/5000</td>
<td>25/25</td>
<td>460/600</td>
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</table>

* Top figure represents results after cure at room temperature for 7 days and bottom figure after cure for 16 hours at 180 degrees F.
The attenuator box had two functions:

1. apply a voltage to the potentiometers,
2. reduce the signal amplitude from the potentiometers to a level compatible with the galvanometers of the strip chart recorder.

The first function was accomplished using a commercially available sealed 30 volt power supply.

The second function was accomplished with care because if too much current was drawn from the potentiometers (the word means potential or voltage measuring) the voltage being measured would be changed by the current flow, causing non-linearities in the measurement. Of key importance is the size of the resistor in the circuit removing current from the potentiometer. If this resistor is too small in comparison to the resistance of the potentiometer then excessive current is drawn from the potentiometer making it function non-linearly. The following then is a derivation of a formula that will relate the linearity of measurement to the size of resistor used in the signal circuit.

Figure 45 shows a simplified circuit diagram of the potentiometer (voltage \( V_1 \) across it) and the signal circuit (\( V_2 \) voltage drop). \( R_1 \) and \( R_2 \) always total the value of resistance of the potentiometer but these values vary as the potentiometer shaft is turned. \( V_1 \) is applied to the potentiometer and \( V_2 \) is the measured output. \( I, I_1, I_2 \) are currents flowing in each section of the circuit. \( R_3 \) is the resistance of the signal circuit.
Using one of Kirchhoff's laws the following equation can be written:

\[ I = I_1 + I_2 \] .......................... (1)

or

\[ \frac{V_1 - V_2}{R_1} = \frac{V_2}{R_2} + \frac{V_2}{R_3} \] .......................... (2)

where a direct substitution of the general relationship,

\[ V = IR \] or \[ I = \frac{V}{R} \] .......................... (3)

has been made into (1). Rewriting (2) gives:

\[ \frac{V_1}{R_1} = V_2 \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right) \]

or

\[ V_2 = V_1 \left( \frac{R_2R_3}{R_2R_3 + R_1R_2 + R_1R_3} \right) \] .......................... (4)
The potentiometers used in this work were 10 turn, 10 K ohm. Therefore $R_1 + R_2 = 10$ K ohm. $V_1$ was 30 volts. By varying $R_3$ for different $R_1 - R_2$ values (resistance change for a given angular change) the following curves can be generated.

Figure 46 shows how the potentiometer output becomes progressively non-linear as the signal resistor, $R_3$, is reduced in size from 50 K ohm to 1 K ohm. Each 1 K ohm on the $R_1 - R_2$ axis represents one shaft revolution.

Figure 47 shows the virtually linear response of the potentiometer when less than one half of a shaft revolution is used to take measurements. In this work all angular measurements were under a 100°, less than one third of a shaft revolution, a resistive change of less than 300 ohms. The potentiometers used in this work could therefore (with $R_3$ a minimum of 2.5 K ohms) be considered as linear as the manufacturer's specifications, that is, 0.2% linear.

The circuit diagram for the attenuator box is shown in Figure 48. The minimum $R_3$ value is 2.5 K ohms if the variable resistors have a 0 ohm value. The 60 ohm resistor across the output plugs was sized by:

1. Obtaining a nominal value for this shunt resistor that controls the electromagnetic damping of the strip chart galvanometers, from the recorder manual, and

2. Experimenting with other similar resistor values until the maximum amplitude output signal was obtained with the minimum noise.

The 1000 K ohm variable resistors were used to adjust the signal amplitude for each attenuator box channel at the time of potentiometer calibration.
Figure 46: 10 turns of the potentiometer shaft (1 K ohm per turn) versus signal output voltage $V_2$. 
Figure 47: The linear output of the potentiometer when the potentiometer shaft is rotated less than half a turn (less than 180 degrees).
Figure 48: Attenuator Box circuit diagram (all resistance values in ohms).
APPENDIX VI - Redesigned Parallelogram Chain

Figure 49: Redesigned parallelogram chain pattern currently being machined.