NOTICE

The quality of this microfiche is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us a poor photocopy.

Previously copyrighted materials (journal articles, published tests, etc.) are not filmed.

Reproduction in full or in part of this film is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30. Please read the authorization forms which accompany this thesis.

THIS DISSERTATION
HAS BEEN MICROFILMED
EXACTLY AS RECEIVED

AVIS

La qualité de cette microfiche dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de mauvaise qualité.

Les documents qui font déjà l'objet d'un droit d'auteur (articles de revue, examens publiés, etc.) ne sont pas microfilmés.

La reproduction, même partielle, de ce microfilm est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30. Veuillez prendre connaissance des formules d'autorisation qui accompagnent cette thèse.

LA THÈSE A ÉTÉ
MICROFILMÉE TELLE QUE
NOUS L'AVONS REÇUE

A PORTABLE ELECTROGONIOMETRIC SYSTEM FOR MONITORING KNEE ANGLE DURING TWO SELECTED WATER SKI FIGURES

by

Jennifer Ann Chrystman
B.A., B.P.E., McMaster University, 1977

A thesis
presented to University of Ottawa
in partial fulfillment of the
requirements for the degree of
Master of Science
in
Department of Kinanthropology

Ottawa, Ontario, 1981

I hereby declare that I am the sole author of this thesis.

I authorize University of Ottawa to lend this thesis to other institutions or individuals for the purpose of scholarly research.

Jennifer Ann Chrystman

I further authorize University of Ottawa to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Jennifer Ann Chrystman

University of Ottawa requires the signatures of all persons using or photocopying this thesis. Please sign below, and give address and date.

ABSTRACT

The purpose of this study was to develop a valid and reliable, portable electrogoniometric system. The subproblem was to apply the portable system in the investigation of knee flexion-extension during the toe back and toe front water ski figures.

Simple elgon construction was chosen for the study and portability of the system was accomplished through the use of the Teledyne 9400 electronic chip as the basis for voltage-to-frequency conversion. Reliability of the system was determined through multiple calibrations of the components and the test-retest correlations were 0.99. Validity of the portable elgons was established in the laboratory through the correlation of elgon and film analysis of a controlled planar movement. Bicycle ergometer pedalling at three different speeds was conducted with five subjects contributing to a total of 30 trials. Leg and thigh angles of inclination were obtained from film analysis using a Vanguard film analyser and computer analysis of this data indicated real time and knee angles. Elgon output was recorded on cassette tape, processed through a frequency-to-voltage converter and hard copy goniographs were produced through a Honeywell vis-

icorder. A computer program was written to analyse the digital elgon data. The real time and knee angles were then matched with the output from the film data and correlations between the film and elgon data for 23 trials were completed using the CORMAT computer program.

The left elgon-film correlations were 0.98, 0.99 and 0.99 for speeds one, two and three respectively. Right elgon-film correlations were 0.96, 0.97 and 0.96 for speeds one to three and these values reflect the validity of the portable electrogoniometric system as defined by high positive relationship with planar film analysis.

Throughout the on-water sessions, knee angle was monitored during the performance of the toe back and toe front water ski figures. Four subjects participated in the study and data from three subjects were available for analysis. Goniographs were produced in the same manner as those from the laboratory tests and analysis was conducted by hand. Correlations between movement time and knee angle indicated the following: movement time of the toe back-toe front sequence was inversely proportional to the range of knee angle of the support leg (r= -0.76); movement time was inversely related to flexion of the rope leg (r= -0.77 and -0.56); and range of knee angle of the rope leg was positively related to movement time during the figures (r= 0.86).

ACKNOWLEGEMENTS

The investigator wishes to express appreciation to A.T. Reed, D.A. Dainty, and W.E. Morrison for their excellent technical and editorial advice throughout this study.

Special thanks go also to Mr. Ben Carraro and Mr. Murray Bickerson of the Department of Electrical Engineering at the University of Ottawa for their technical help and generosity with both time and laboratory equipment.

DEDICATION

And such confidence we have through Christ towards God. Not that we are adequate in ourselves to consider anything as coming from ourselves, but our adequacy is from God, who also made us adequate as servants of a new covenant, not of the letter, but of the Spirit; for the letter kills, but the Spirit gives life.

2 Corinthians 3:4-6

CONTENTS

Appendix

LIST OF TABLES

LIST OF FIGURES

Chapter I

THE PROBLEM

1.1 INTRODUCTION

For years, kinesiologists have studied the kinematics of a wide variety of sport skills. An understanding of the movement patterns based on scientific analysis is now recognized as a foundation for coaching (Hay, 1973). Many sports have not had the advantages of this scientific base however, since the athletes must perform in a specific environment not conducive to investigation.

Some outdoor sports have benefited through the application of film techniques. The method is most successful with sport events in which the athlete's movements are confined to a known area of small dimensions. Other research methods such as electrogoniometry have traditionally been limited to use in a laboratory setting (Adrian and Karpovich, 1964; Finley and Karpovich, 1964). Development of a portable electrogoniometer system would allow the application of this research method to outdoor sports and could then be used even in situations not conducive to film analysis of sport kinematics.

Water skiing is an outdoor sport involving complex motion and has therefore not benefited from rigorous movement analysis. Popular articles and books on water ski coaching refer only in a general way to the movements involved in each event (Andresen, 1960; Tyll, 1966; Stephens, 1974; Athans and Ward, 1975; Nations and Desmond, 1977; Barnes et.al., 1978; Krupa, Snow and McLeod, 1978.). These coaching directives are based on simple observation of athletes or film sequences rather than any quantitative biomechanical studies. Competitive water skiing is therefore in need of scientifically based coaching material similar to that of other sports.

Because of the nature of the sport, competitive water skiing is not easily adapted to laboratory testing. A few indoor pully systems have been designed for use in a swimming pool (Oshogin, 1975), and water jet tanks have also been developed for skiing (Hardman(ed), 1975a; Hardman(ed), 1975b). Since almost all competitive training is done on the open water however, there is a need to monitor performance variables in this outdoor setting.

Film analysis is a very popular research tool in the study of sport kinematics. In the study of a complex non-planar movement such as water skiing, film from three cameras would be needed for analysis (Miller and Nelson, 1973). The environment of water skiing imposed severe limitations on its utilization however. Problems related to the use of film in this setting included camera positioning, synchronization of cameras, control of the subject's planar motion through the field of view, and the measurement of all factors related to camera-subject distance.

Stationary camera placement required that the testing area have suitable shoreline positions surrounding, and in reasonable proximity to the boat path. Cameras needed to be positioned so that the joints to be analysed were always in view of at least two of the three cameras, and because of the rotational nature of the skier's movements, cameras would have had to be placed on opposite shorelines in order to fulfill these criteria.

Shapiro (1978) stated that the main problem with multi-camera filming was the need to measure all factors related to external camera orientation and felt that at least six non-coplanar control points were needed to control for the sources of error. Van Gheluwe (1975) also mentioned the need to take several measurements of target points. The difficulty of acquiring these measures in the given environment was a definite drawback to the use of film.

Another difficulty with the use of film was the synchronization of film views. Laboratory filming is usually synchronized through the use of two or three dimensional timing devices which are situated within camera views

(Blievernicht, 1967; Miller and Nelson, 1973). These clocks were designed for use with alternating current power sources and were not easily adapted to a marine environment..

Film was also not a practical testing technique in light of the fact that the movement to be analysed was planar. Knee flexion-extension is two dimensional by definition and is the only major action of the knee, since it is a condylar hinge joint (Anthony and Kolthoff, 1971). Using a three dimensional filming method to analyse planar motion was not practical when electrogoniometry was available to isolate the knee flexion-extension. Electrogoniometry avoided the difficulties inherent in tri-dimensional filming, provided data which was simple to reduce, and also supplied a permanent record for later study and analysis. Electrogoniometry was therefore chosen for the study of knee flexion-extension during two selected water ski figures.

The two water ski figures chosen for study were the toe back and toe front. These are the basic toe turns performed in the figures event of water skiing and their performance forms the basis for advanced figures necessary in top level competition. During performance of the figures, the pulling force of the boat is transmitted to the skier through the ski rope and rope leg. It is through proper control of this force by the rope leg that the skier rotates his body and turns the ski from a front to back position. There is both a strength and flexibility component involved in the knee flexion-extension in the rope leg as the skier controls the rate of ski rotation through manipulation of the pulling force.

1.2 STATEMENT OF THE PROBLEM

The problem was to develop and establish the validity and reliability of a portable electrogoniometric recording system. A sub-problem was to apply the system in the analysis of water skiing; specifically, to investigate the knee flexion-extension present throughout the "toe back" and "toe front" water ski figures.

1.3 HYPOTHESIS

The hypothesis is that the portable elgon system will provide valid and reliable measures of knee angle during the performance of selected water ski figures.

1.4 LIMITATIONS

The study was designed to deal with the development and application of portable electrogoniometry in the figures event of competitive water skiing. Personal communication with international skiers and coaches (Messner and Messner, 1978; Stiffler, 1975) indicated that knee angle during the selected figures would not exceed the range of zero to 90 degrees of flexion. Angular limitations of zero to 90 degrees were therefore accepted for the validity and reliability testing. Personal communication with coaches (Messner and Messner, 1978) also led the investigator to estimate the frequency of knee movement as below the 0.5 Hertz level. For this reason, the elgons were tested within the 0.25 to 0.67 Hertz frequency range.

For reasons previously stated, the toe back and toe front were chosen for inclusion in the study and only the angles of knee flexion-extension were monitored throughout the performance of these figures. Three subjects of intermediate and national calibre contributed to the analysed data of the toe back-toe front. The results of this portion of the study are therefore applicable to the performance of the toe back-toe front by competitive athletes of similar skill level.

With regard to the portable electrogoniometry, several restrictions were inherent. Since the elgons were of rigid rather than hinged design, they were most suited to subjects having moderate musculature about the knee joint. The need for shielded cables connecting the elgons and recording equipment added to the weight of the ski rope. While this variable did not cause serious problems for the athletes, it's effect on the performance of the figures is not known.

1.5 DEFINITION OF TERMS

The electrogoniometer (elgon) is a device which provides a direct and continuous electrical output proportional to angular joint displacements. The functional unit of the elgon is a potentiometer which varies the resistance to the voltage input as the shaft of the potentiometer is rotated by the elgon arms, thus causing a variable voltage output.

The Teledyne 9400 V/F circuit is an electronic chip which performs a voltage-to-frequency conversion of an input signal.

The Teledyne 9400 F/V circuit is an electronic chip which performs a frequency-to-voltage conversion of an input signal.

Zero degrees of knee flexion is defined as full extension of the knee joint, at which position the thigh and leg segments form a straight line.

Ninety degrees of knee flexion is defined as the position at which the thigh and leg segments are at right angles to each other.

The toe back (TB) water ski figure consists of a 180 degree rotation of the ski from a front to back position. It must be performed on one ski with the non-supporting foot harnessed to the ski rope via a toe strap.

The toe front (TF) water ski figure consists of a 180 degree rotation of the ski from a back to front position, with the criteria for foot position similar to that of the toe back.

The support leg is defined as the leg to which the ski is attached. Weight bearing is its main function.

The rope leg is defined as the leg which is connected to the ski rope by the toe strap. Its main function is to control the pull from the boat and help maintain balance.

Chapter II

REVIEW OF THE LITERATURE

2.1 INTRODUCTION

The areas to be covered relate directly to the choice and design of the electrogoniometric equipment, its validity, reliability, and use in monitoring knee angle during two selected water ski figures.

A review of the electrogoniometry literature gave an overview of this device's use in sport research. The literature also dealt with the variety of elgon construction and waterproofing methods, the validity and reliability of elgons as a measuring device, and the portability of the recording system. The water ski coaching material reflected the lack of scientific research in this sport and illuminated the area of concern to which the sub-problem of this thesis was directed.

2.2 ELECTROGONIOMETRY

The electrogoniometer or elgon is a device similar to a protractor which measures changes in joint angle. As the arms of the elgon move in a planar motion, they rotate the shaft of a potentiometer causing variable resistance to an input voltage. The resulting output is a voltage which varies directly as the angular position of the elgon arms.

Elgons have been used extensively in research on joint actions including: flexion-extension of the knee, ankle, wrist, elbow, hip, finger, big toe; and pronation-supination of the forearm and foot (Adrian, 1968). They have been used in the study of joint action during such activities as walking, running, somersaulting, swimming, long jumping, high jumping, and triple jumping (Gollnick and Karpovich, 1964; Adrian and Karpovich, 1966; Klissouras and Karpovich, 1967; Singer and Adrian, 1969).

2.2.1 Construction and Waterproofing

Several methods have been used in the construction of elgons. Some researchers designed a separate chassis to which the potentiometer was attached with snap buttons (Finley and Karpovich, 1964). Others (Adrian and Karpovich, 1964; Kettelkamp et.al., 1970), used a hinged chassis design which allowed for lateral movement of the potentiometer. The angular position of the elgon was therefore unaffected by varied amounts of musculature around a joint. Peat et.al. (1976) also designed a gravity reference elgon for use in measuring single plane arm movements. As the arm segment moved, a weighted pendulum would remain vertical and rotate the shaft of the potentiometer.

In the simple elgon construction, the chassis was attached directly to the potentiometer, and the arms were rigid rather than hinged (Huntinger, 1971; Singh and Ashton, 1970). An example of this type of construction is shown in Figure 1. A variation of this design was also used by McLeod et.al. (1975) in which the rigid arms were constructed of wires.

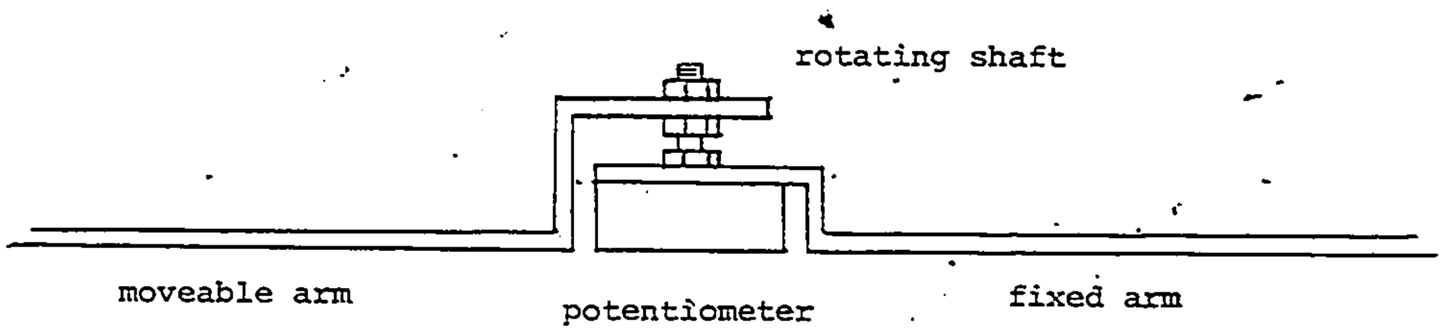


Figure 1: Simple Elgon Construction

Two methods have been used for the waterproofing of elgons. Ringer and Adrian (1969) enclosed the potentiometer within a rubber balloon, sealing the ends of the balloon with a silicone rubber adhesive, and Gollnick and Karpovich (1964) covered the potentiometer with epoxy, providing a water tight seal. Since neither article mentioned any problems with water leakage into the potentiometer, it can be assumed that both methods provided a suitable waterproof seal.

2.2.2 Elgon Alignment

Most researchers agreed on the alignment of the elgon for accurate recording of knee angle. The potentiometer was placed on the lateral epicondyle of the femur with its arms on a line connecting the lateral epicondyle with the mid-point of the greater trochanter and the mid-point of the lateral malleolus (Gollnick, Tipton and Karpovich, 1964; Tipton and Karpovich, 1965). Kettelkamp et.al. (1970) were the only researchers to position the potentiometer at a point midway between the lateral epicondyle of the femur and the joint line. A diagram of the knee joint by Clauser McConville and Young (1969) can be found in Appendix A.1 on page 54 and shows the bony structure of the knee joint and the axis of rotation.

Related to the question of elgon placement was that of measurement validity from a joint which does not have a stationary axis of rotation (Teager and Somerset, 1976). Korb (1970) stated that since elgons move about a single axis of rotation, they "do not account for the fact that the axis of rotation of a bony joint is not fixed, but travels within the joint as it moves" (Korb, 1970, p.205).

Although the axis of rotation tends to migrate, this occurs within a relatively small area. The area is so small in fact, that Blacharski and Somerset (1975) concluded from their kinematic study of the knee that "the joint could be replaced with a prosthesis having a three dimensional axis of rotation with a fixed centre." (Blacharski and Somerset, 1975 p.383). While mention is made of the secondary joint actions of the knee, the suitability of a fixed rotational centre supports the contention that elgons are valid in the study of knee flexion-extention. An example of the elgon alignment used in this study can be found in Appendix A.2 on page 55.

2.2.3 Validity and Reliability

Kettelkamp et.al. (1970) validated the elgon measures by roentgenographic examination. The calculation of the errors related to the position of the elgons indicated that an acceptable degree of accuracy was achieved. Since the migration of the joint centre occurred within a 25 millimeter sphere, the magnitude of correction for flexion and extension did not exceed two degrees. This study by Kettelkamp revealed that the goniometric technique was valid for approximating knee motion.

The elgon validation technique of Karpovich, Herden and Asa (1960) was based on a comparison of the elgon with a manual goniometer and angles formed by intersecting rods attached to the limb segments. Subjects were seated on a table having a goniometer secured in the saggital plane. The knee was aligned with the centre of the goniometer and both electrical and manual readings were taken for a variety of angles.

Metal rods were also attached to the thigh and leg segments, and their angle of intersection at the knee joint was measured and compared to the elgon output. The validity of this latter technique was poor however, when used with cadaver segments and subjected to roentgenographic examination. The investigators concluded that the rods did not give an exact indication of knee angles. The method was not precise in estimating knee angle and therefore not suitable for use as an accurate validation method for electrogoniometry.

Film analysis has been used as a validation technique (Adrian, 1971) and was most beneficial when used with a controlled planar movement. Although film analysis is a widely accepted validation technique, there is a conspicuous lack of quantitative material in the literature to indicate the validity of electrogoniometry as compared to film. While researchers have spent considerable time constructing and calibrating elgons, there were few articles dealing with the validation techniques of this research tool.

Reliability of the electrogoniometric method was investigated by Johnston and Smidt (1969) and the test-retest differences were within the zero to four degree range. Ketelkamp et.al. (1970) reported test-retest differences of zero to 8.5 degrees. None of the differences in either study were significant at the .05 level.

2.2.4 Portability

With the exception of the study by McLeod et.al. (1975), portability of electrogoniometry has not been documented. One researcher relied on lead wires and a pully system, when needed, to control excessive lengths of the wire and prevent its interference with movement (Adrian, 1971).

McLeod et.al. (1975) addressed the problem of elgon portability and designed a system to deal with this problem. The recording electronic circuits consisted of a voltage controlled oscillator and a reference oscillator. The circuit-recorder unit was very small and attached directly to the subject while the elgon recordings were made (McLeod et.al., 1975). The signals were then electrically added and recorded on tape.

In the playback circuits, the frequencies from the two oscillators were separated by phase-locked loops. These loops monitored the change in phase angle resulting from a change in frequency and produced an output voltage corresponding to the change. The phase-locked loops therefore acted as frequency-to-voltage converters (Malmstadt, Enke and Crouch, 1974).

2.3 WATER SKIING

The water ski coaching information available was qualitative in its description of the toe back and toe front. Coaching directives acknowlege the importance of leg movements in controlling the performance of the figures, and refer to the knee action in general terms. Due to the tight neoprene and rubber bindings on trick skis, the range of movement of the ankle is minimized. The power to unweight the ski during a turn is produced mainly by the hip and knee extension which act simultaneously. Authors agreed on basic knee action of both the rope leg and support leg, but were not specific as to the angle or range of angles present (Athans and Ward, 1975; Stephens, 1974; Krupa,Snow and McLeod, 1978).

In reference to the support leg, Tyll (1966) said to bounce up and down, implying at least some unweighting and range of knee flexion of the support leg throughout the figures. Athans and Ward (1975) and Barnes et.al. (1978) also instructed the skier to bounce and unweight the ski, although again, the specific range of knee angle was not given. Stephens (1974) mentioned a hop in the unweighting process and Andresen (1960) refered to this action as rising up on the support leg. Krupa, Snow and McLeod (1978) instructed the skier to initiate the turn with a slight hop and then keep the support leg bent throughout the turn.

None of the instruction gave a quantitative description of the knee movement throughout the figures. Bouncing up and down may be the same action as weighting and unweighting, but since they were both subjective statements, the knee actions cannot be compared. What is needed is a quantitative description of the knee flexion-extension of the support leg, to provide a basis for specific coaching directives.

While the complete rope leg position was mentioned by all the authors, only Athans and Ward (1975) and Stephens (1974) described the knee angle of this leg. Both authors spoke of the rope leg knee as bent, but neither commented on whether this angle was static or dynamic. Nations and Desmond (1977) said that the foot holding the rope must be held close to the support leg throughout the figures. Andresen (1960) instructed the skier to pull in the rope with his leg so that the knees were close together, but the actions of the knee were not mentioned. Krupa, Snow and McLeod (1978) mentioned that a fall could be caused by straightening the knee of the rope leg, thus implying that knee flexion in the rope leg should be maintained throughout the performance of the figures.

The descriptions of knee angle of both the support leg and rope leg were inadequate since they were not specific in a quantitative manner. No mention was made as to the angle or range of angles through which the knee moved in flexion-extension, and these are the ambiguities to which the sub-problem of this thesis was directed.

2.4 SUMMARY

The material presented in this chapter formed the historical background and rationale for the elgon construction, waterproofing, and validation testing in this research. It also outlined the method of voltage-to-frequency conversion previously utilized for portable recording, and the need for kinematic research in figures event of competitive water skiing.

The simple elgon construction of Huntinger (1971) was useful for monitoring joint action of athletes. Literature also indicated that waterproofing with a flexible sealant protected the electrical equipment from water damage. Since the centre of knee joint rotation migrated within a very small area, elgons were capable of giving a valid indication of joint angle. The elgon alignment most commonly used was that of Gollnick, Tipton and Karpovich (1964).

Film analysis of planar movement was one of the best methods for the validity testing of the elgons.

Chapter III

METHODOLOGY

3.1 ELGON CONSTRUCTION AND WATERPROOFING

The simple elgon construction of Huntinger (1971) was followed. The potentiometers used were 4 watt, 250 ohm type, and the potentiometer shafts were machined (threaded) so that the aluminum elgon arms could be fastened securely with lock washers and nuts. Excess shaft length was then removed to prevent possible injury or inconvenience in handling. Having secured the aluminum arms to the potentiometers, the elgons were wired to 50 foot tri-axial cables with ground mesh shield. When connected to a 9 volt power source, the voltage drop across the length of cable was 0.04 volts.

A flexible seal of silicone rubber was applied to the potentiometer and shaft area of the elgons. Rotation of the elgon arms was not restricted by the sealant and calibration of the elgons from zero to 90 degrees of flexion was completed. Although rotation of the elgon arms through less than zero degrees was possible, this angular range was not calibrated since the likelihood of this range of knee joint movement during the skiing was considered to be nil.

3.2 RECORDING SYSTEM

In order to record the data on cassette tape as frequency modulating signals, voltage to frequency conversion was necessary. This was accomplished through the use of the Teledyne 9400 electronic chip. Teledyne Co. (1977) designed a converter which performs the same function as the equipment of McLeod et.al. (1975).

The Teledyne 9400 is a circuit chip capable of voltage-to-frequency conversion which "accepts a variable analog input signal and generates as output pulse train whose frequency is linearly proportional to the input voltage" (Teledyne Semiconductor 9400, p.1). The Teledyne 9400 can also form the foundation for a frequency-to-voltage converter capable of accepting "virtually any input frequency waveform and providing a linearly proportional voltage output" (Teledyne Semiconductor 9400, p.1).

Since construction of a complete converter required only the addition of resistors, capacitors, and a reference voltage to the Teledyne 9400 chip, the converter was simple to construct, inexpensive, and highly reliable. For these reasons, the Teledyne 9400 was chosen as the foundation for the portable electrogoniometric system of this research. The required circuitry was assembled in duplicate on a fibreglass electronics board and housed in a mini-box. (A circuit diagram of the complete voltage-to-frequency converter may be found in Appendix B.1 on page 56.) The connectors used were BNC jacks and plugs.

The recording system for the portable electrogoniometry consisted of several components; battery power source, voltage regulator, input resistors, elgons and cables, voltage to frequency circuits, and a portable cassette recorder. A flow chart of the recording system components is shown in Figure 2. Voltage output of the battery was approximately 12 volts and the voltage regulator was adjusted to provide 9.0 volts output for the recording circuits.

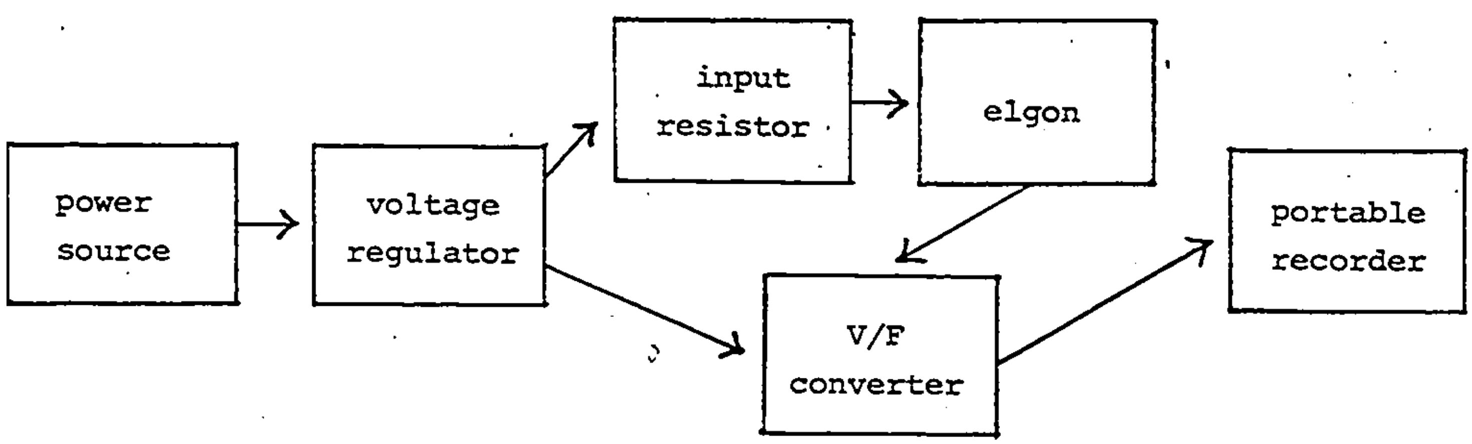


Figure 2: Recording System Components

The input resistors of 1K ohms were housed in a mini-box. Telephone jacks were used to connect the tri-axial cables with these input resistors, so the circuit could be easily broken at this point when necessary. Thoughout the on-water sessions, there was a possibility of subjects falling, in which case the elgon-cable-ski rope unit would need to be released from the boat so as not to drag the skier. Telephone jacks could be rapidly pulled from the mini-box without causing any damage to the box or connectors, and therefore reduced the possibilities of equipment damage.

3.3 CALIBRATION

Calibration of the V/F and F/V circuits was completed in the laboratory with the use of a variable voltage power source, a Fluke 1900A digital frequency counter, a Wavetek 182 function generator, and a Balantine 3030A multimeter.

Initial calibration of the elgons was completed in the laboratory using a 9.0 volt power source. One elgon arm was secured to a large board upon which was drawn a 90 degree range of protracted angles. Each elgon was calibrated at five degree intervals from zero to 90 degrees, since this was the maximum range of angles expected to occur during the water ski monitoring. Calibration was repeated before the on-water monitoring session.

Each component in the recording system provided linear output. Although the output from the analysis components was not linear from 0 to 90 degrees, linearity between each of the five degree calibration intervals was assumed. Accuracy of the elgons was therefore not limited by the calibration interval values. Elgon output was analysed to the nearest 0.5 degrees. Figure 3 shows a graph of the calibration curve for the analysis system.

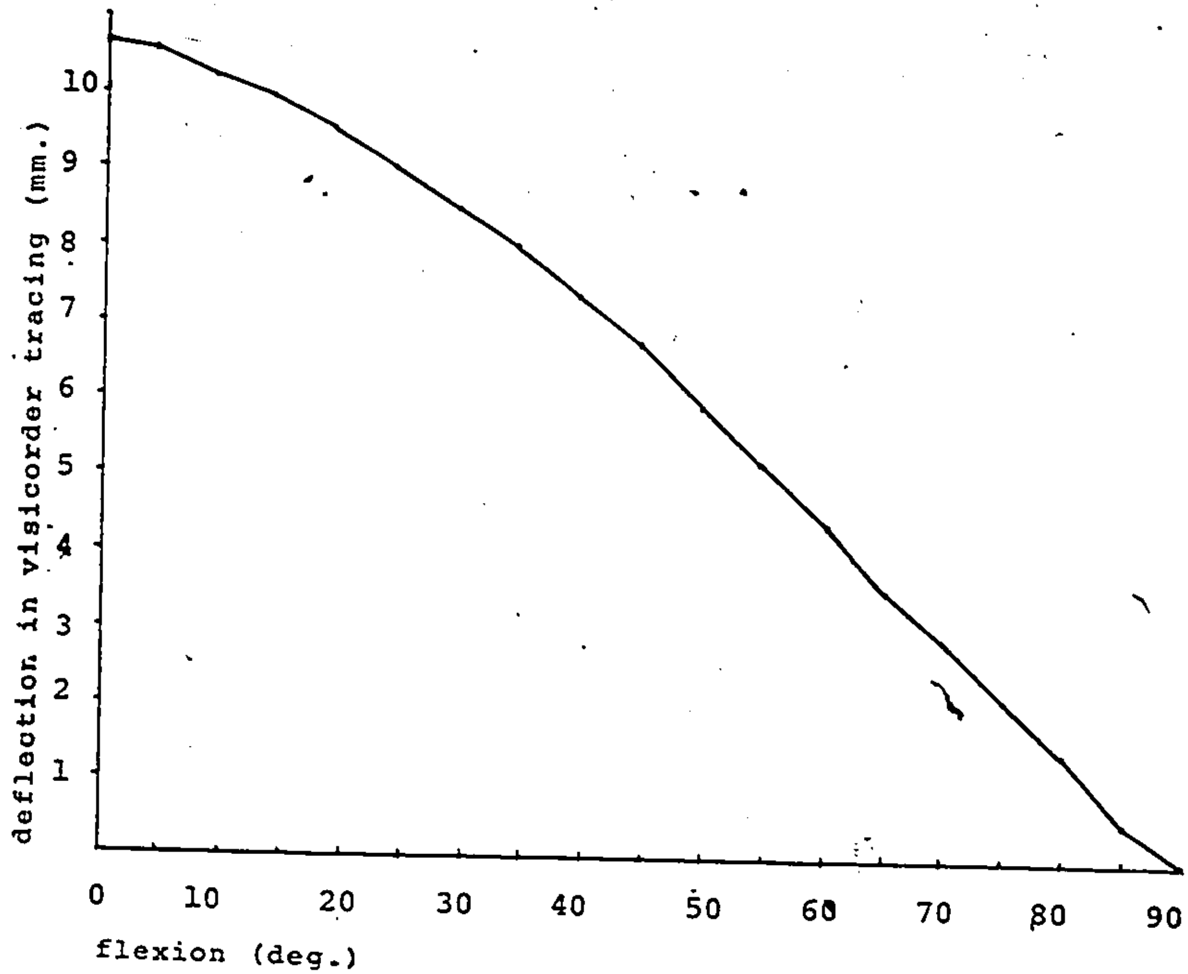


Figure 3: Analysis System Calibration Curve

3.4 VALIDITY AND RELIABILITY TESTING

Film analysis was the technique used to evaluate validity of the portable elgon system. Bicycle ergometer pedalling was chosen as the uni-planar movement to be performed since the range of knee angles throughout the pedalling was sufficiently large to correspond to those monitored during the on-water sessions.

Five subjects participated in the testing and each performed three consecutive trials on a Monarch bicycle ergometer. The speed of pedalling was indicated by a metronome, with the subjects instructed to match the beat with the alternating full extension of each leg. Trial one was performed at 60 beats per minute and this corresponded to a rate of a half cycle per second. Trial two was performed at 120 beats per minute or one cycle per second, and trial three was completed at 160 beats per minute or 1.33 cycles per second. During one cycle of pedalling, the elgon would move through an optimal range of 0 to 90 to 0 degrees, or a total of 180 degrees of motion. Therefore, at bicycling rates of 0.5, 1.0 and 1.33 cycles per second, the average elgon frequency was 0.25, 0.5 and 0.67 cycles per second (Hz.).

Illumination of the subjects was provided by three 1000 watt Ianabeam quartz lamps. The bicycle ergometer was positioned perpendicularly to the optical axis of the camera at a distance of 24 feet from the camera. The camera used was a Bolex H16 spring driven, reflex model with a two factor shutter and had a Berthiot lens with a focal length of 35mm. The film was 16 mm TXR with an ASA rating of 160 tungsten. Frame rate was set at 64 frames per second and the calculated f-stop was 8. Synchronization of film and electrical signals was accomplished through the use of a microswitch which was located on the sprocket of the ergometer. Black markers were placed behind the crank and aligned so that a marker on the crank would indicate the position at which the microswitch engaged.

3.5 WATER SKI TESTING

Monitoring of knee angle during the two selected water ski figures was completed with the use of a Ski Nautique competition water ski boat and a Cassad trick release. The monitoring equipment was set up in the boat, with the mini-box of input resistors secured to the boat's pylon directly below the trick release.

The 50 foot cables were attached to the ski rope and trick handle with adhesive tape. Several large loops of cable were secured to the ski rope with surgical tubing. Since the tubing could stretch and allow the elgons to move away from the trick handle and toe harness, this gave the skier more freedom to manoeuvre without pulling the cables away from the elgons. The cables were also extended three feet past the handle to provide for the appropriate distance between the toe harness and the skier's knees.

A timing mark was included on a separate channel of the tape recorder to indicate the time during which subjects were performing the toe back and toe front figures. A continuous signal was recorded from the onset of the toe back to the completion of the toe front. A Bolex H16 reflex camera was also used during the on-water sessions as a source of qualitative information about the movements occurring during the figures performance, thus providing information related to the movement time of each figure. The camera was hand-held in the boat approximately 45 feet from the skier, and the film speed was 16 frames per second.

Four subjects ranging in expertise from intermediate to international calibre, participated in the on-water session. Unintended damage to the elgons and failure of the water-proof seal to protect the potentiometers resulted in the loss of data for the fourth subject, however. Elgon output from three subjects was therefore available for analysis.

Skiers were briefed before the trials as to the nature of the testing and the boat-to-skier signals which would be used to indicate the onset of the monitoring procedures. The lateral epicondyles of both the right and left femurs were located and marked and the potentiometers were positioned according to the alignment suggested by Gollnick, Tipton and Karpovich (1964). A picture showing this alignment can be found in Appendix A.2 on page 55. The arms of the elgons were then secured to the calf and thigh with several strips of adhesive tape. The subject was asked to flex and extend each knee to assure adequate range of motion and investigate possible shifting of the potentiometer during movement.

3.6 METHODS OF ANALYSIS

A Vanguard Motion Analyser with pin registration was used to obtain information from the laboratory test film. Throughout each trial, the angles of inclination of the thigh and leg were estimated, and recorded along with the corresponding frame number. These values were then used as input data for a computer analysis program which calculated the real knee angle and the time of each measure.

The elgon frequency output on cassette tape was replayed through the Teledyne 9400 frequency-to-voltage converter and amplifier circuit. (A circuit diagram of the complete frequency-to-voltage converter may be found in Appendix B.2 on page 57.) The voltage was recorded on light sensitive paper by a Honeywell 1508B visicorder and the graphs were converted from analog signal to digital data by a Gardicon digitizer. A flow chart of the analysis system components is shown in Figure 4.

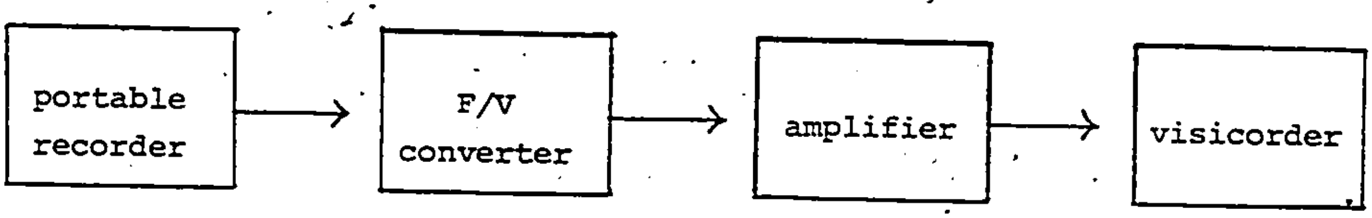


Figure 4: Analysis System Components

The digital data was then used as input for computer analysis. The program was designed to read the calibration values and test data and calculate the real knee angles and the real time at which they occurred. Data from the film analysis and analog signals were then paired by matching the real time values. These comparison values were submitted to the Correlation Matrix (CORMAT) Instapack computer program. The input variables for this program were knee angle from film and elgon, and the output indicated the correlation between these. Correlation values were then used as a representation of the validity of the portable electrogoniometric system.

Elgon recordings from the on-water sessions were converted to voltage modulated signals and transferred to light sensitive paper in the same way as those of the laboratory sessions. The calibration scale was then added to each graph and the following information calculated; maximum knee angle, minimum knee angle, range of knee angle and movement time of the toe back-toe front. Statistically, the data was analysed by the Correlation Matrix (CORMAT) computer program. The following correlations were noted for both the rope leg and support leg; movement time and maximum knee angle, movement time and minimum knee angle, movement time and range of knee angle. Since speed of movement is most important to competitive figures performance, the time variable was correlated with knee angle. Minimum, maximum and range of knee angle were the factors chosen as best indicators of knee flexion-extension present throughout the figures.

Chapter IV

RESULTS

4.1 EQUIPMENT CALIBRATION

With a 9 volt power source, the left elgon output varied from 0.985 to 1.597 volts and the output from the right elgon varied between 1.280 and 1.810 volts. Output from the left elgon was processed by channel one of the V/F converter and resulted in an output range of 0.903 to 1.313 kHz. Voltage output from the right elgon was processed by V/F channel two with a resulting output range of 0.891 to 1.255 kHz. These frquency signals were then recorded and stored on cassette tape.

The frquency modulating signals from both left elgon-channel one and right elgon-channel two were processed through one F/V circuit and amplifier. For the range of 1.891 to 1.313 kHz. input, the output of the F/V circuit varied between 5.446 volts and 5.595 volts. The amplifier was adjusted to give the best amplification of this voltage range for signal processing through the visicorder. A #1650 galvonometer was used in the selected recording channel to minimize attenuation of the signal.

4.2 RELIABILITY OF THE PORTABLE ELGON EQUIPMENT

The left elgon calibration data were most complete and used as input data for the CORMAT program. Correlation of the test-retest calibration values was 0.99, indicating an extremely high reliability for the elgons.

Both channels of the V/F circuit were calibrated three times. Calibration values for both V/F circuits were entered into the CORMAT program and the resulting correlations were 0.99 for both channels one and two. This indicates a very high reliability for these circuits. The F/V circuit calibration also resulted in correlations of 0.99 and showed high reliability for the frequency-to-voltage converter.

4.3 ESTIMATE OF MEASUREMENT ERROR

Measurement error in digitizing was estimated by repeated measure of an arbitrary length of one second, with the origin (0,0) reset before each of the 10 measurements. The raw digital output values ranged from 4952 to 4966 machine units (m.u.), with a mean of 4957 and a standard deviation of 4.64 m.u. Since the smallest 0.5 degree calibration range was more than 20 m.u. in length, an average error of 5 units would have an insignificant effect on the calculation of knee angle from the electrogoniographs. During one trial there was a range of over 9000 m.u. during the flexion- extension of the elgons. Measurement error of five m.u. would therefore result in less than a 0.1 percent error.

An error of 4.64 m.u. could affect the calculation of real time by as much as 0.0009 seconds for each of the trials however. From digitized data, it was estimated that as little as 0.0004 seconds elapsed between 0.5 angle change, and an error of 0.0009 seconds could therefore affect the calculation of knee angle by 1.0 degree when the digitized data were paired with the data from film. This could cause a slight phase shift in the data and result in a discrepency between film and algon results.

In order to estimate the measurement reliability of digitizing the electrogoniographs, one trial was digitized three times, with the origin (0,0) reset before each curve tracing was performed. A computer program was written to analyse the data and the resulting "real knee angles" were matched according to the second output variable of "real time". Knee angle values were then entered into CORMAT and the resulting correlation values of 0.99 reflect the high reliability with which the elgon data was digitized.

Measurement reliability in film analysis was estimated by repeated measure of both thigh and leg segment angles of inclination and subsequent calculation of knee angle. The 10 estimates of knee angle ranged from 56.0 to 59.0 degrees, with an average of 57.5 and a standard deviation of 1.09 degrees.

4.4 VALIDITY OF THE PORTABLE ELGON SYSTEM

Validity of the portable elgon system was established through the analysis of 23 trials. One cycle per trial was chosen for analysis. This choice was based both on the clarity of the film and the completeness of the cycles as they appeared in the electrical recording. Since the first and last cycles were usually incomplete, one of the middle two cycles was used for analysis. The chosen sections of the goniograph were marked appropriately before digitizing and were then analysed within the zero to 90 degree angle range. A computer analysis program was written with a ceiling value of 90 degrees so that all values greater than this would be automatically assigned the real value of 90.

Thigh and leg inclination values from film were analysed every other frame for the trials performed at a half cycle per second. The same values were recorded for every frame of the one and 1.33 cycle per second trials. On the average, this resulted in the recording of 49 frames per cycle. In order to pair the elgon and film data, the time duration of each trial was taken from the electrical tracings and the appropriate time scale factor was then used in the computer programs for the analysis of film data.

Within the zero to 90 degree range of real values, the time and knee angle of every second score was noted from the film analysis program. These real time values were then paired with identical time values in the electrical data and the corresponding knee angles were recorded. The data for each trial was therefore reduced to real time and real knee angle from both film and electrogoniometry. An example of this paired data can be found in Table 1

TABLE 1

Film and Elgon Data for Subject 1 Trial 1 During Bicycle Pedalling in the Laboratory

Time (sec)	Film (degrees)	Elgon (degrees)
0.2388	89.0	84.5
0.3123	81.0	76.5
0.3857	72.0	69.5
0.4592	64.5	61.5
0.5327	57.0	53.0
0.6062	50.0	46.5
0.6796	43.5	41.0
0.7531	41.0	38.0
0.8266	42.0	39.0
0.9001	46.5	43.0
0.9735	53.5	50.0
1.0470	60.5	57.5
1.1205	67.0	61.5
1.1940	75.0	68.0
1.2674	83.5	75.0
1.3409	90.0	81.0

These three scores were entered into CORMAT for each elgon at each of the three test speeds and correlations between film and elgon analysis were very high for both the right and the left elgons. The left elgon-film correlations were 0.98, 0.99 and 0.99 for speeds one, two and three respectively. The right elgon-film correlations were 0.96, 0.97 and 0.96 for speeds one to three and indicate the high validity of the portable electrogoniometric system as defined by high positive relationship with planar film analysis.

As can be seen from the values presented in Table 1, the raw scores at each time point are not identical. The difference between the film and elgon measures varied both between elgons and subjects. The average errors for the left and right elgons were 3.3 and 10.2 degrees respectively.

4.5 ANALYSIS OF WATER SKI FIGURES

Data from three of the four subjects monitored during water ski figures was used in the analysis. Damage to the elgons during the on-water sessions prevented adequate data collection from the fourth subject and therefore reduced the number of trials to nine for each of the toe back and toe front.

Time estimates for the figures were taken from the event markers recorded in the electrical data. The calibration scale was transfered to the graph of each trial and the following values were recorded; movement time for the toe back-toe front sequence, minimum knee angle and maximum knee angle. Range of knee angle was then calculated for each trial from the minimum and maximum knee angles.

The movement time for the toe back-toe front varied between subjects but consistently decreased from trials one to three for each of the subjects. The average movement times were 1.72, 1.29 and 1.58 seconds respectively for subjects one, two and three. For the support leg, minimum knee angle varied between 2.5 degrees for subject two and 36.5 degrees for subject three and the average minimum angle for all subjects was 19.5 degrees. The maximum knee angle varied between 27.5 degrees for subject one and 57 degrees for subject three with the average for all subjects being 40.5 degrees. The range of knee angle for the support leg varied from 10.5 to 32.5 degrees with an average value of 21 degrees. These data are summarized in Table 2

For the rope leg, variation in knee angle between subjects was much more noticeable. While angle varied quite consistently from 0 to 58.5 degrees for subject one, both subjects two and three had a maximum knee angle in excess of 90 degrees. The minimum knee angle of subjects two and three varied between 40 degrees for subject three and 82.5 degrees for subject two, with an average of 59.8 degrees. The variation in range of knee angle for all three subjects was 7.5 to 59 degrees and the average angle range was 39.5 degrees. These data for the rope leg are summarized in Table 3

TABLE 2

Movement Factors of the Support Leg During Toe Back-Toe Front

Subj.	Trial	Time	Min. Angle	Max. Angle	Range
1	1	1.90	17.0	27.5	10.5
	2	1.65	18.0	37.5	19.5
	3	1.60	22.0	32.0	10.0
2	1	1.50	6.0	32.0	26.0
	2	1.28	5.0	33.0	28.0
	3	1.08	2.5	35.0	32.5
3	1	1.80	33.0	55.0	22.0
	2	1.55	36.0	57.0	21.0
	3	1.40	36.5	56.0	19.5

TABLE 3

Movement Factors of the Rope Leg During Toe Back-Toe Front

Subj.	Trial	Time	Min. Angle	Max. Angle	Range
1	1	1.90	0	58.5	58.5
	2	1.65	0	59.0	59.0
	3	1.60	0	58.0	58.0
2	1	1.50	59.0	90.0	31.0
	2	1.28	68.5	90.0	21.5
	3	1.08	82.5	90.0	7.5
3	1	1.80	47.0	90.0	43.0
	2	1.55	40.0	90.0	50.0
	3	1.40	62.0	90.0	28.0

Movement time, minimum angle, maximum angle and range of knee angle were the four values per leg which were submitted to CORMAT. For the support leg, correlation between movement time and range of knee angle was -0.76, while neither correlation between time and minimum or maximum knee angle were better than r= 0.50. The value of -0.76 indicated that there was an inverse relationship between movement time and range of knee angle of the support leg. For the rope leg, correlation between movement time and minimum knee angle was -0.77 and correlation between movement time and maximum knee angle was -0.56. These results showed an inverse relationship between movement time and flexion of the rope leg. The correlation between movement time and range of knee angle of the rope leg was 0.86 and this showed a very positive relationship between these two factors.

Chapter V

DISCUSSION

Simple elgon construction was used in this research and provided valid estimates of knee angle. The silicone waterproofing material tended to leak during the on-water sessions and was not suitable as a sealant. Although the exact location of the leak was unknown, it may have occurred either around the potentiometer shaft or in the cable attachment area. Rotation of the shaft through more than 90 degrees during the on-water sessions may also be related to the failure of the silicone gel to maintain a proper seal. This finding does not support the literature indicating that a direct application of sealant would provide a water resistant seal for the potentiometers (Gollnick and Karpovich, 1964).

High reliability of the equipment components (r= 0.99) supported the assumption that the Teledyne 9400 would provide an excellent basis for high quality voltage-to-frequency and frequency-to-voltage conversion. Although the voltage output of the analysis system was not linear, this limitation was overcome through slight modificaton of the computer analysis programs for the goniographs. Calibration of the elgons in the zero to 90 degree range proved to be less than ideal for the purposes of this study. Knee flexion in excess of 90 degrees was recorded from the rope leg in two of the three subjects but could not be estimated due to the calibration restrictions and the lack of linearity in the output of the analysis system. These data contradicted the personal communication with international calibre coaches (Messner and Messner, 1978; Stiffler, 1975) which suggested that knee angle would not exceed 90 degrees of flexion.

Bicycle ergometer pedalling provided an excellent planar movement for the validation testing and range of knee angle during the sessions was as great as 10-100 degrees of flexion. The maximum frequency of knee flexion-extension observed during the performance of the toe back and toe front was 0.56 Hz. Since the frequency of the elgon flexion-extension throughout the lab testing was 0.25, 0.5 and 0.67 Hz., the frequency range was well chosen.

Measurement error in digitizing was sufficient to cause a 0.0009 second phase shift in the elgon data and as much as a one degree change in knee angle values. The phase shift was not evident however, in the analysis of data. The discrepency between paired elgon and film data was more likely to have resulted from measurement error in the film analysis, error in the placement of the elgons, or slippage of the elgons during the monitoring sessions.

The average error for the left elgon was approximately three degrees and of this, one degree can be accounted for by each of the digitizing and film analysis measurement errors. The remaining degree of error is most likely due to the error in placement of the elgon. The average error between the film and right elgon data was approximately 10 degrees. While two degrees can again be accounted for by measurement error in film analysing and goniograph digitizing, the remaining eight degrees error are most probably due to slippage of the elgon. Six of the nine trials used for analysis were recorded after the subject had already completed the monitoring of the left elgon. The fact that the subjects had already been pedalling intermittantly for five or ten minutes and had moved about between trials may have accounted for some loosening of the adhesive tape which secured the elgon arms to the leg and thigh segments. This error is not surprising however, when compared to the 8.5 degree difference in test-retest elgon outputs reported by Kettelkamp et. al. (1970).

The values of maximum, minimum and range of knee angle used were chosen as factors in the analysis of water ski data since they related to the the coaching directives. The unweighting of the ski by the support leg would have involved a range of knee flexion, while the suggestion to keep the rope leg close to the support leg would possibly have indicated a static knee angle for the rope leg.

The inverse relationship (r= -0.76) between movement time of the water ski figures and range of angle of the support leg meant that a larger range of knee angle was related to faster performance of the figures. This fact supported the view that skiers unweight the ski (Athans and Ward, 1975; Barnes et.al., 1978) and that they do in fact "bounce up and down" or "hop" (Tyll, 1966; Krupa, Snow and McLeod, 1978). The greatest range of flexion-extension recorded for the support leg was 32.5 degrees and occurred during the trial having the fastest movement time (1.08 seconds). Within the limitations of this study therefore, the optimal range was 32.5 degrees.

Correlations of 0.46 and 0.04 between movement time and minimum and maximum knee angle respectively indicated that neither of these factors were related to the performance speed of the toe back-toe front. Specific knee angle of the support leg was not mentioned in any of the coaching material, and therefore these data did not support one coaching method above any other.

The correlations (r= -0.77, r= -0.56) between movement time and minimum and maximum knee flexion of the rope leg indicated that faster movement time is related to greater flexion of the rope leg. This means that the speed with which the figures were performed was directly related to knee flexion of the rope leg. Correlation between maximum angle and movement time (r= -0.56) was lower than expected and may have resulted from the calibration ceiling of 90 degrees which was exceeded during six of the nine trials.

The correlation relating speed of movement to flexion of the rope leg supported the literature which instructed the skier to bend the rope leg (Athans and Ward, 1975; Stephens, 1974). The extent of this flexion was in excess of 90 degrees and the minimum knee flexion associated with the fastest movement time in this study was 82.5 degrees. This indicated that the rope leg knee should remain in a flexed position throughout the toe back-toe front sequence in order to facilitate movement speed.

The positive relationship (r= 0.86) between movement time and range of knee angle indicated that a faster completion of the figures was related to a constant knee angle as opposed to a wide variation in angle of the rope leg. This tended to support the coaching directives of Nations and Desmond (1977) who said that the rope leg must be held close to the support leg. It also indicated that static knee angle in doing so was advantageous. Within the limitations of this research, a small range of knee flexion of the rope leg was shown to facilitate speed of movement in the two selected figures.

Knee flexion of the rope leg in excess of 90 degrees indicated that national and international calibre coaches are not capable of correctly estimating the knee actions which occur during figures performance. This fact reinforces the importance of quantitative research in the figures event of competitive water skiing.

Chapter VI

SUMMARY, CONCLUSIONS AND DISCUSSION

6.1 SUMMARY

This thesis research was directed toward the problem of developing a valid and reliable portable electrogoniometric system. The subproblem was to apply the portable system in monitoring knee angle during the toe back and toe front competitive water ski figures.

Simple elgon construction was chosen for the study and portability of the system was accomplished through the use of the Teledyne 9400 electronic chip as the basis for voltage-to-frequency and frequency-to-voltage conversion. Validity of the system was established through high positive relationship between elgon recordings and film analysis of a controlled planar movement. Bicycle ergometer pedalling at three different speeds was conducted with five subjects contributing to a total of 30 trials.

Multiple calibrations of each component of the system and the subsequent correlations of 0.99 indicated the high reliability of the equipment. Analysis of 23 trials and correlations between film and elgon data resulted in P.P.M.

values greater than 0.98 and 0.96 for the left and right elgons respectively and reflected the high validity of the portable elgon system.

Four subjects were used in the monitoring of knee angle during the selected water ski figures. Of the 15 trials recorded, nine were suitable for analysis, and correlations between movement time and knee angle indicated the following: movement time of the toe back-toe front sequence was inversely proportional to the range of knee angle of the support leg (r= -0.76); movement time was inversely related to minimum and maximum angles of flexion of the rope leg (r= -0.77 and r= -0.56); and range of knee angle of the rope leg was positively related to movement time during the figures (r= 0.86).

6.2 CONCLUSIONS

Within the limitations of this thesis, the following conclusions can be made:

1. Validity of the portable elgon system was high, as reflected by the elgon-film correlation values.

2. High reliability of the portable electrogoniometry was indicated by the test-retest calibration values.

3. Movement speed of the figures was associated with increased range of knee flexion-extension of the support leg.

4. Movement speed of the figures was associated with greater knee flexion of the rope leg as well as a decreased range of flexion-extension in this knee.

6.3 RECOMMENDATIONS FOR FUTURE STUDY

The recommendations outlined here are related to the choice and design of monitoring components, the calibration procedures, selection of a validation technique, and the choice of subjects. Their implementation would improve both the quality of the research itself and the extent to which the results would be applicable to the sport of water skiing.

Although the use of simple elgon construction was very effective in this study, the use of hinged elgons would allow for monitoring of subjects having greater amounts of musculature around the knee joint. Male athletes of national team calibre could then be included in the on-water sessions and their contribution to the data would be benificial.

The use of lighter weight cable connecting the elgons and recording equipment is also recommended since it would have minimal effect on the subsequent weight of the ski rope and the performance of the figures. The use of telemetry for the transmission of data would also decrease any movement restrictions caused by cables.

Calibration of the elgons should exceed the zero to 90 degree range used in this study. Although the necessary calibration range is not known, the elgons should possibly be calibrated to as much as 135 degrees of flexion. This would allow for accurate calculation of knee angle thoughout the range most likely to occur during the performance of the selected water ski figures.

The range of knee angle occurring during ergometer pedalling would not be adequate for proper validation of a greater range in elgon flexion. Instead, it is recommended that simple knee flexion be utilized during which the leg segment move 135 degrees between two padded stops or bars. A metronome could still be used to help control angular velocity and a microswitch could be secured to each bar to provide for synchronization of film and electrical recordings. This test method would allow for validation of a greater flexion range and yet maintain the simplicity of necessary laboratory equipment. It is also recommended that a loop of adhesive tape be secured to the elgon arms before they are attached to the leg and thigh segments to reduce slippage of the elgons.

It would be advantageous if the number of subjects could be increased for the on-water sessions. The results of the water ski sessions would then have more application to the coaching directives in the figures event, since the sampling could include a wider range of skiing expertise from the population. The use of national team calibre athletes in the water ski sessions would also be benificial since knee angle during optimal performance of the figures could be accomplished.

BIBLIOGRAPHY

Adrian, M. "Electrogoniometry," Biomechanics. Chicago: The Athletic Institute, 85-89, 1971.

Adrian, M. "An Introduction to Electrogoniometry," Kinesiology Review Washington: AAHPER, 12-17, 1968.

Adrian, M., Karpovich, P.V. "Effect of Walking in Cowboy Boots on the Knee Action," Research Quarterly. 35: 398-402, 1964.

Adrian, M., Karpovich, P.V. "Foot Instability During Walking in Shoes with High Heels," Research Quarterly 37: 168-175, 1966.

Andresen, J. Skiing on Water. New York: Ronald, 1960.

Anthony, C.P., Kolthoff, N.J. Textbook of Anatomy and Physiology. St. Louis: Mosby, 1971.

Athans, G., Ward, C. Water Skiing. Toronto: Collier-McMillan, 1975.

Barnes, R., Bush, S., Messner, P., Reid, B., Reid, K. Canadian Water Ski Association Level II: Coaches Manual. Ottawa; C.W.S.A., 1978.

Blacharski, P.A., Somerset, J.H. "A Three Dimensional Study of the Kinematics of the Human Knee," J. of Biomechanics. 8: 375-384, 1975.

Blievernicht, D.L. "A Multidimensional Timing Device for Cinematography," Research Quarterly. 38: 146-148, 1967.

Clauser, C.E., McConville, J.T., Young, J.W. Weight, Volume, and Centre of Mass of Segments of the Human Body. Ohio: Wright-Patterson Air Force Base, 1969.

Finley, F.R., Karpovich, P.V. "Electrogoniometric Analysis of Normal and Pathalogical Gaits," Research Quarterly. 35: 379-384, 1964.

Gollnick, P.D., Karpovich, P.V. "Electrogoniometric Study of Locomotion and of Some Athletic Movements," Research Quarterly. 35: 357-369, 1964.

Gollnick,P.D., Tipton,C.M., Karpovich,P.V. "Electrogoniometric Study of Walking on High Heels," Reasearch Quarterly. 35: 370-378, 1964.

Hardman,T.C. (ed.) "Bald Eagle Show Time," The Water Skier. 3: 20, 1975.

Hardman,T.C. (ed.) "Poolside Ski Tricking," The Water Skier. 3: 42, 1975.

Hay,J.G. The Biomechanics of Sport Techniques. Englewood Cliffs N.J.: Prentice-Hall, 1973.

Huntinger,P.W. "Construction and Utilization of a Simple Electrogoniometer," Biomechanics. Chicago: The Athletic Institute, 91-97, 1971.

Johnston,R.C., Smidt,G.L. "Measurement of Hip Joint Motion During Walking. Evaluation of an Electrogoniometric Method," J. Bone Jnt. Surgery. 51A: 1083-1094, 1969.

Karpovich,P.V., Herden,E.L., Asa,M.M. "Electrogoniometric Study of Joints," U.S. Armed Forces Med.J. 11: 424- , 1960.

Kettelkamp,D.B., Johnson,R.J., Smidt,G.L., Chao,E.Y.S., Walker,M. "An Electrogoniometric Study of Knee Motion in Normal Gait," J.Bone Jnt. Surgery. 52A: 775-790, 1970.

Klissouras,V., Karpovich,P.V. "Electrogoniometric Study of Jumping Events," Research Quarterly. 38: 41-48, 1967.

Korb,R.J. "A Simple Electrogoniometer: A Technical Note," Research Quarterly. 41: 203-205, 1970.

Krupa,T., Snow,T., McLeod,H. Ski Tips. Winter Park: Water Motions Inc., 1978.

Malmstadt,H.V., Enke,C.G., Crouch,S.R. Electronic Measurements for Scientists. Menlo Park: W.A. Benjamin Inc., 1974.

McLeod,P.C., Kettelkamp,D.B., Srinivasan,V., Henderson,O.L. "Measurements of Repetitive Activities of the Knee," J.of Biomechanics. 8: 369-373, 1975.

Messner,P.M., Messner,J.A. personal communication, 1978.

Miller,D.I., Nelson,R.C. Biomechanics of Sport. Philadelphia: Lea & Febiger, 1973.

Nations,D., Desmond,K. Guiness Guide to Water Skiing. Middlesex: Guiness Superlatives Ltd., 1977.

Oshogin,V.I. "A Progress Report on Skiing in the Soviet Union," The Water Skier. 4: 23-28, 1975.

Peat,M., Grahame,R.E., Fulford,R., Quanbury,A.O. "An Electrogoniometer for the Measurement of Single Plane Movements," J.of Biomechanics. 9: 423-424, 1976.

Ringer,L.B., Adrian,M. "An Electrogoniometric Study of the Wrist and Elbow in the Crawl Arm Stroke," Research Quarterly. 40: 353-363, 1969.

Shapiro,R. "Direct Linear Transformation Method for Three-Dimensional Cinematography," Research Quarterly. 49: 197-205, 1978.

Singh,M., Ashton,T.E.J. "Study of Back Lift Strength with Electrogoniometric Analysis of Hip Angle," Research Quarterly. 41: 562-568, 1970.

Stephens,K. Water Skiing. Toronto: McGraw-Hill Ryerson, 1974.

Stiffler,F. personal communication, 1975.

Teager,T., Somerset,J.H. "Investigation of the Error Caused by Femur Movement Attendant to an In Vivo Study of Human Knees," J.of Biomechanics. 9: 659-661, 1976.

Teledyne Co. "Voltage to Frequency, Frequency to Voltage Converter 9400," Teledyne Semiconductor. Mountainview, Cal.: (Aug.) 1977.

Tipton,C.M., Karpovich,P.V. "Electrogoniometric Records of Knee and Ankle Movements in Pathological Gaits," Arch.Phys.Med. and Rehab. 46: 267-272, 1965.

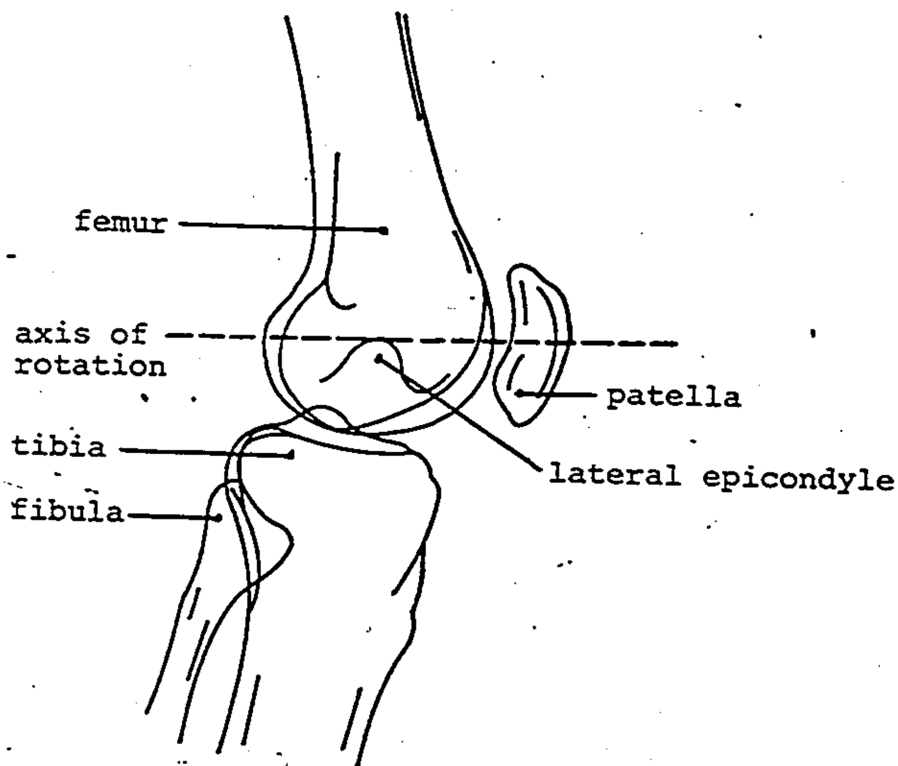
Tyll,A. Water Skiing. New York: Arco, 1966.

Van Gheluwe,B. "Errors Caused by Misalignment of the Cameras in Cinematographical Analyses," Research Quarterly. 46: 153-161, 1975.

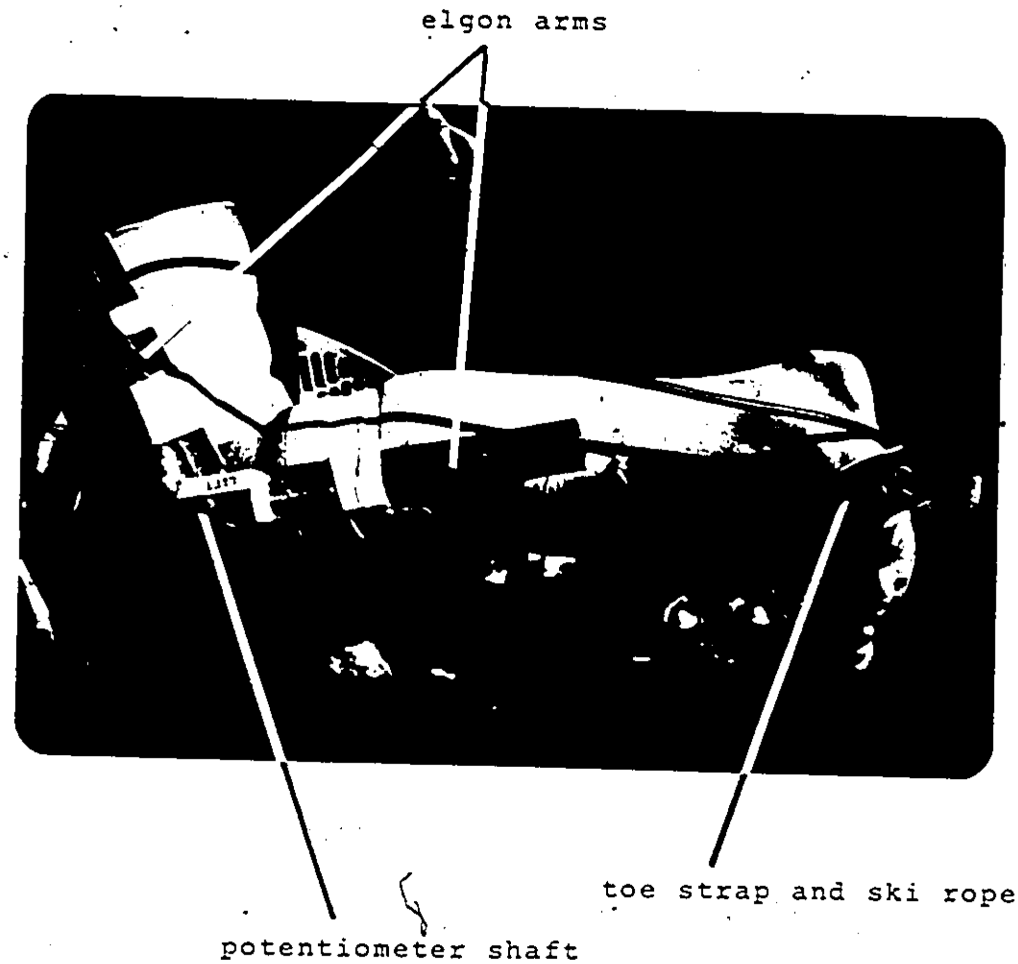
Appendix A

ELGON PLACEMENT

A.1 KNEE JOINT DIAGRAM



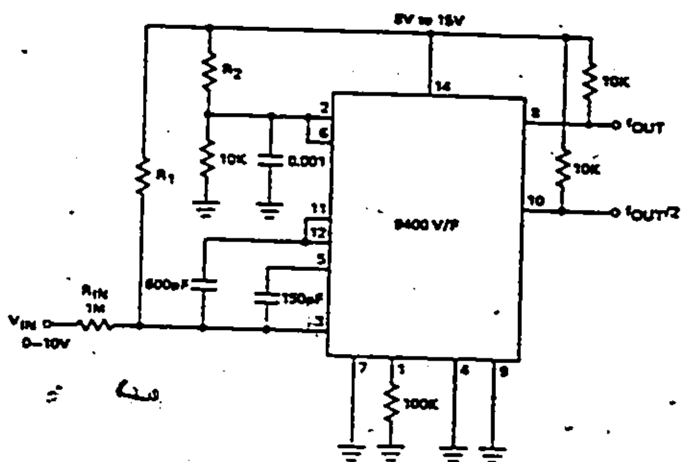
A.2 ELGON ALIGNMENT



Appendix B

ELECTRONIC COMPONENTS AND CIRCUITRY

B.1 VOLTAGE-TO-FREQUENCY CIRCUIT



B.2 FREQUENCY-TO-VOLTAGE CIRCUIT