FOOT ARCH CHARACTERISTICS AND LOWER LIMB OVERUSE INJURIES IN HABITUALLY BAREFOOT AND SHOD KENYAN ADOLESCENTS.

BY

DR PAUL MAKOKHA OKUTOYI

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DECLARATION

Declaration by candidate:

This thesis is my original work and has not been presented for a degree in any other university. No part of this thesis may be reproduced without prior written permission of the author and or Moi University.

Signature Date

Declaration by the supervisors:

This thesis has been submitted with our approval as university supervisors.

Dr. Lectary K. Lelei

Name of supervisor Signature Date

Dr. Neford Ongaro

Name of supervisor Signature Date

DEDICATION

I wish to dedicate this study to my lovely family, who have ever been supportive and with whose kind words and actions of encouragement I was able to complete the study.

I also wish to thank the almighty God for having given me the wisdom and faith in carrying out this research.

ABSTRACT

Title: Foot arch characteristics and lower limb overuse injuries in habitually barefoot and shod Kenyan adolescents.

Background: The barefoot habitus typical of early human lifestyles may cause intrinsic foot structural adaptations which could protect lower limbs from impact related overuse injuries.

Objective : This study sought to assess foot arch height and flexibility, intrinsic foot muscle strength and prevalence of the common lower limb overuse injuries in habitually barefoot, rural school going adolescents; in comparison to an age, weight and sex matched group from a shod population.

Methodology: This was a cross-sectional study conducted in both rural Nandi for the habitually barefoot and a modern setting for the shod group. 38 habitually barefoot (HB) and 38 age, gender and weight matched habitually shod adolescents (HS) were investigated for foot arch characteristics, intrinsic foot muscle strength and lower limb overuse injury prevalence. Arch height at 50% of foot length was measured seated and standing by an arch height index measurement system, and relative arch deformability computed. Intrinsic foot muscle strength was measured using a commercially available foot strength electronic dynamometer. Physical activity was quantified using uni-axial accelerometry. Injury incidence was interrogated via a structured questionnaire and physical examination.

Results: The foot arch was higher and more flexible in the HB compared to HS. (Arch height 6.7{5.6, 8.1} vs. 6.2{4.6, 7.2} p= 0.01; Relative arch deformability 0.76{0.58, 1.063} vs. 0.64{0.41, 0.79} p= 0.012, respectively). The HB had stronger intrinsic foot muscles (IFM) than the HS (IFM strength 4.7kgs {3.10, 6.13} vs. 3.30kgs {2.18, 4.35} p= 0.03). There was a higher lower limb overuse injury incidence rate in the HS (28.8% vs. 2.6%, chi-square 9.896, p<0.02). There was no statistically significant correlation between gender, physical activity levels and the measured foot arch characteristics.

Conclusions and recommendations: In comparison to shod adolescents, the habitually barefoot were found to have a higher, more flexible medial longitudinal foot arch and stronger foot intrinsic musculature. They also recorded a lower incidence of lower limb overuse injuries. Further prospective studies are recommended to relate the morphological foot differences found between HB and HS, and overuse injuries in all active age groups.

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Herje Aibast was involved in data collection and analysis. Timothy Sigei, Dr. Walter Adero, Danny Chemjor contributed to data collection. Dr.Neford Ongaro contributed office space in his hospital. Noriyuki Fuku provided the foot strength device. Dr. Kenn Konstabel created the algorithms used for the analysis of raw accelerometer outputs. Steve Simiyu was involved in the statistical analysis of the data. Professor Daniel E. Lieberman provided the arch index measuring system and was involved in data interpretation. Professor Yannis Pitsiladis availed the accelerometers, and contributed to data interpretation.

God Bless you all.

ACRONYMS

AHIMS – arch height index measuring system

HB – habitually barefoot

HS – habitually shod

IFM – intrinsic foot muscles

ITBS – ilio-tibial band syndrome

MLA – medial longitudinal arch

MTSS - medial tibial stress syndrome

MVPA – moderate to vigorous physical activity

PFP – patello-femoral pain

RAD – relative arch deformability

DEFINITION OF TERMS

Accelerometry - measurement of the quantity and frequency of human movement.

Anthropometry - the science dealing with measurement of the size, weight, and proportions of the human body.

Biomechanics – The study of the mechanics of a living body, especially of the forces exerted by muscles and gravity on the skeletal structure.

Cadaveric – Relating to a dead body.

Fascia - a sheet or band of fibrous tissue such as lies deep to the skin or invests muscles and various body organs.

Intrinsic – situated entirely within or pertaining exclusively to a part.

Isometric - involving muscular contraction against resistance in which the length of the muscle remains the same.

Habitual – done as an aquired behavioural pattern.

Morphologic – the form and structure of organisms without consideration of function.

Plantar - pertaining to the sole of the foot.

Shod – wearing shoes.

Somatosensory - pertaining to sensations received in the skin and deep tissues.

Tarsal – pertaining to the area of articulation between the foot and the leg.

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CHAPTER 1: INTRODUCTION

The foot is complex in both its structure and function. It consists of 28 bones and 33 articulations, each with several degrees of freedom. The structure of the foot allows it to act as a shock attenuator during early and midstance and a rigid lever during push-off. Integrity of the foot structure, including all bones, joints, ligaments and muscles, is critical in ensuring optimal function when walking, running and jumping.

The foot is able to cushion impact forces during ambulation due to its arches. The arches are formed by a unique alignment of the bones, muscles, tendons, and ligaments allowing for functional adaptability. They allow the foot to support the weight of the body in the erect posture with the least weight. The medial longitudinal arch (MLA) is the primary shock-absorbing structure of the foot hence of particular importance for foot functions.[1]

The natural state of the foot, i.e., the bare foot, has been studied by several investigators. Hoffman in the early 1900's examined the feet of 186 natives of the Philippines and Central Africa who had never worn shoes.[2] He concluded that the foot form, function and range of voluntary and passive motion are the same in both the habitually barefoot and habitually shod up to the time of shoe-wearing, after which progressive characteristic deformation and inhibition of function ensue. Engle and Morton studied the feet of unshod natives in the Belgian Congo. They found an absence of static foot deformities and noticed that the major foot problems were due to parasitic infections and trauma.[3] These findings were reflected by James, who studied the footprints of natives of the Solomon Islands.[4] Finally, Sim-Fook and Hodgson compared 118 shoe wearing and 107 non-shoe-wearing Chinese. They found that the feet of the barefoot subjects showed greater mobility and fewer deformities than of those wearing shoes.[5] These studies consistently showed that the unshod human foot is characterized by: (1) excellent mobility, especially of the forefoot; (2) creases on both the plantar and dorsum of the foot due to the flexibility of the midtarsal joints and (3) an absence of static deformity. On the other hand, shoe wearing may lead to development of various foot deformities and aberrations in foot function. Frey et al. reported that 88% of the healthy women surveyed were wearing shoes smaller than their feet, and that 80% of them had some sort of foot deformity.[6]

The use of footwear from early childhood may substantially influence foot structure and give rise to static foot deformities. Common deformities reported in literature include bunions and callosities, hallux valgus, hammer toe and symptomatic flat feet. Some studies have found an inverse relationship between foot mobility/flexibility and foot deformities.[5]

Staheli conducted extensive research on arch development and pediatric shoe wear. His studies conclude the following: (1) Optimum foot development occurs in the barefoot environment, (2) Stiff and compressive footwear may cause deformity, weakness, and loss of mobility.[7]

Changes in foot structure, some of which have been associated with shoe wearing as highlighted in the preceding prose may in turn influence the biomechanics of the foot and lower limb and seemingly cause injuries. High foot arches have been proposed to increase the likelihood of injuries to bones, the ankle and lateral injuries. Low arches on the other hand, have been associated with higher risk of soft tissue, knee and medial injuries.[8] Kaufman et al. found dynamic pes planus, pes cavus and restricted ankle dorsi flexion to be risk factors for lower extremity overuse injuries.[9]

An overuse injury occurs when a structure is exposed to a large number of repetitive micro trauma and forces. The incidence of running-related repetitive stress injuries stands between 30% and 70% per year according to western reports.[10, 11].This is unacceptably high, yet there is no consensus on how to prevent these injuries.

From an evolution perspective, it is proposed that the human body has evolved over time to suit barefoot running. Bramble and Lieberman[12] argue that humans have been running long distances for millions of years, and, obviously, most of that running was done barefoot on hard, rough surfaces. Minimal shoes, such as sandals or moccasins, were probably invented in the Upper Paleolithic, which began only about 45,000 years ago.[13] Everyone including athletes ran barefoot or in minimal shoes until the 1970s when the modern running shoe with a cushioned heel, arch support, and stiffened sole was invented. Since then, running shoes have often been blamed for the increased incidence of running injuries and a considerable number of runners have switched to barefoot running for relief from chronic injuries.[14]

Studying the morphology of the foot in a habitually barefoot population thus should be the basis of understanding the etiology and pathomechanics of overuse injuries of the lower limbs using a cause- effect model. This would then play a pivotal role in managing and preventing these injuries.

CHAPTER 2: LITERATURE REVIEW

a) Foot structure.

Methods of describing foot structure or foot type are typically based on the measurement of morphological parameters of the foot, mostly in the standing weight-bearing position, or during locomotion. The medial longitudinal arch (MLA) is the largest and most important arch of the foot from a clinical point of view. Based on the structure of the medial longitudinal arch, three foot types have been proposed: [15, 16] (1) normally aligned or normal foot, (2) low arched or pronated foot, or pes planus, and (3) high arched or supinated foot, or pes cavus. Normally aligned foot is defined as the foot in which the bisection of the posterior surface of the calcaneus is perpendicular to the ground and its arch height is within normal range. Pronated foot is defined as the foot in which the calcaneus is everted and its arch is low or absent. Supinated foot is defined as the foot in which the calcaneus is inverted and its arch is high. The supinated foot is more rigid with limited shock absorption ability, prone to higher stress underneath the heel and more force passing to the tibia and femur. The pronated foot, with a greater ground contact area, is more flexible, leading to the load being absorbed by the musculoskeletal structures of the foot. There are many methods of quantifying the MLA. The methods fall under the following main categories: Visual non quantitative inspection, foot print assessment, photographic, radiologic and anthropometric measurements using calipers. The most widely used methods of anthropometric quantification of the arch height include navicular height and foot dorsum height.

b) Variations in foot structure among the habitually barefoot and shod populations.

Assessment and description of foot types is almost a century old, yet it has still not been well established if, or to what extent, the habitually shod foot is different from the habitually barefoot. Hoffmann in 1905, using a limited sample size, noticed that habitual, or native, barefoot walkers universally have wider toe regions, a trend he also observed in classical sculptures. He linked such anatomy to the use of non-constricting sandals in antiquity. Interestingly, he also describes that only a few weeks of shoe-wearing by children already affects foot shape, especially toe placement.[2] It is not surprising that the effect of footwear appears to be greatest during childhood, when the foot is still maturing (i.e. the bones are being ossified and fused).[17] Wells (1931) compared habitually barefoot South African natives to Europeans and described several qualitative differences, e.g. a broader shape and a lower medial arch in the Africans.[18] More recently, a few papers have addressed (mostly rather descriptively) foot shape or function in habitually barefoot populations. Tuttle et al. (1992) and Musiba et al. (1997) studied barefoot walkers from Peru and Tanzania, respectively, and found the feet of these populations to be similar in plantar features, and compatible to those seen in the 3.7-million-year-old Laetoli footprints.[19, 20, 21] Echarri and Forriol (2003), studying Congolese children, found a larger proportion of flatfeet in an urban (predominantly shod) population than in a rural (predominantly barefoot) population.[22] Two other authors, Rao et al(1992) and Sachithanandam (1995) also attributed shoe wearing in early childhood to development of flat foot.[23, 24] Ashizawa et al. (1997) found that habitual barefoot walkers from Java had relatively long and wide feet[25] and, similarly, Sim-Fook and Hodgson (1958) described a relatively spread anterior part of the foot in habitually barefoot Chinese.[5] Kadambande et al. (2006) found that habitually barefoot Indians have more pliant feet than shod British.[26] Rao and Joseph (1992), studying the incidence of flat feet in Indians, found this condition to be most common in children who wore closed-toe shoes, less common in those who wore sandals or slippers, and least in the unshod.[23]

The studies mentioned here typically focused on **qualitative** descriptions of foot shape and did not address quantitative aspects like foot arch height and arch flexibility. Moreover, some did not have suitable control groups. Comparing shod and unshod individuals of the same ethnic background is important, as differences in foot properties between ethnic groups have been described.[18]

c) Intrinsic foot muscles and arch support.

There has been general consensus about the major arch supporting structures being the bones of the midfoot, intrinsic ligaments and fascia, and extrinsic muscles via the long tendons.[27, 28, 29, 30] Cadaveric studies involving the plantar aponeurosis have shown that this structure provides substantial stability to the MLA.[31] There is also more published data that states that the MLA is supported primarily by extrinsic muscles, such as the tibialis posterior.[32, 33] Cadaveric studies focused on the muscles of the lower leg concluded that the various muscles in this region are the primary supporting structures of the MLA.[31] The role of the tibialis posterior muscle is also supported by observations of ruptured posterior tibialis tendon, resulting in traumatic flatfoot.[34, 35]

Intrinsic foot muscle (IFM) activity has recently been an area of great research interest for scientists, physicians and physiotherapists in order to develop improved shoe designs, more effective foot orthotic braces and to prevent overuse injuries. It has been suggested that the basic primary function of the IFM is to permit flexibility for shock absorption and balance, and to provide rigidity and stability for propulsion.[36] Fiolkowski et al. investigated the role of intrinsic muscles of the foot in supporting the MLA, by anesthetizing the posterior tibial nerve at the ankle and quantifying the navicular drop. The results indicated that the intrinsic musculature in the plantar aspect of the foot has a role in supporting the MLA in stance.[37] There are studies that support the role of intrinsic plantar muscles supporting the MLA in a dynamic state like walking (Robbins and Hanna[38], Mann[39]). Although the former study did not directly measure muscle activity, the authors surmised that the MLA changes noted were likely the result of increased activity of the intrinsic plantar musculature. Early studies used electromyography (EMG) and custom built dynamometers to assess isometric foot muscle strength and foot muscle activity during different physical activities.[40, 41] For activation of the foot intrinsic muscles, somatosensory feedback-mechanisms need to be activated and these mechanisms are more developed in habitually barefoot individuals owing to adaptations induced by barefoot activities.[38] Thus, it follows that if the intrinsic muscles are important static and dynamic stabilizers of the MLA, and the barefoot state being a potent stimulator of somatosensory mediated foot structural adaptations during ambulatory activities, this study sought to determine whether the habitually barefoot would have stronger intrinsic muscles.

d) Arch flexibility.

Deformation of foot arch is crucial for force transfer and shock absorption, especially in impact sports, such as jump or sprint. Williams, et al. noted that people with high-arched feet had an increased propensity for bony injury while those with low arched feet had a higher rate of soft-tissue injury.[8] These trends may be related, in part, to the flexibility of the arch. While there are exceptions, low-arched feet often are more flexible, and high arched feet tend to be stiffer. Thus, a flexible, low-arched foot may stretch the soft tissues of the foot as it attempts to generate a sufficient moment for toe-off. Conversely, a high-arched foot may be less mobile and more prone to injuries such as a stress fracture, resulting from a lack of shock attenuation.[42] If arch structure is related to injury, a further understanding of factors influencing arch structure could lend insight into injury mechanisms.

Age has been shown to play a role in arch structure, particularly height and stiffness. Clinicians have reported a higher number of patients with flatfeet in their fifth and sixth decades of life.[43] These observations support the common belief that arches tend to “fall” as people age. In addition to changes in arch height, arch stiffness may change with age. Previous studies have indicated that soft tissues tend to stiffen and osteophytes form with age.[43] These changes can lead to limitations in joint motion. There has been no documented study to the best of my knowledge that compares arch height and flexibility in the habitually barefoot and habitually shod groups from the same population and similar demographic characteristics, like age.

e) Physical activity levels.

Despite many attempts to study the structure and function of the foot, little is known about how foot structure and function can be influenced by habitual physical activity. Very high physical activity levels have been reported in East African children and adolescents,[44, 45, 46, 47] with some studies reporting that Kenyan and Ethiopian children from rural areas run up to 20 km to school daily[48, 49]and are also engaged in physically active leisure time activities and household chores. This high childhood habitual physical activity typically conducted unshod, has been proposed as one of the explanations for the success of Kenyan and Ethiopian runners.[49] It would then make sense to suggest that higher activity levels would be associated with higher prevalence of overuse injuries, due to the repetitive nature of loading of the involved body parts. On the other hand, higher physical activity levels are known to mitigate against acute injuries due to improved physical fitness. No work has attempted to associate activity levels with arch structure and intrinsic foot muscle strength and thus in extension to overuse injuries.

f) Common running related overuse injuries in the lower limbs.

There is no standard definition of an overuse running injury, but several authors have defined it as a musculoskeletal ailment attributed to running that causes a restriction of running speed, distance, duration, or frequency for at least one week.[50, 51, 52] Examples of overuse injuries that commonly occur during running include stress fractures, medial tibial stress (shin splints), chondromalacia patellae, plantar fasciitis, and Achilles tendinitis.

Brief epidemiology of running overuse injuries

According to a recent (2007) thorough systematic review of overuse running injuries,[11] the overall incidence varied from 19.4% to 79.3%. The predominant site of lower extremity injuries was the knee, for which the location specific incidence ranged from 7.2% to 50.0%. Injuries of the lower leg (shin, Achilles tendon, calf, and heel), foot (also toes), and upper leg (hamstring, thigh, and quadriceps) were common, ranging from 9.0% to 32.2%, 5.7% to 39.3%, and 3.4% to 38.1%, respectively. Less common sites of lower extremity injuries were the ankle and the hip/pelvis (also groin), ranging from 3.9% to 16.6% and 3.3% to 11.5%, respectively**.**

Although the exact causes of overuse running injuries have yet to be determined, it can be stated with certainty that the etiology of these injuries is multifactorial and diverse.[53, 54, 55] A large majority of the factors identified as causes of overuse running injuries could be placed into three general categories: **training, anatomical, and biomechanical factors.**

All three of the above factors either alone or in combination may put an individual at an increased risk for injury.[56]

With regards to the habitually barefoot, several authors attribute the condition to better arch development[7], better intrinsic muscle development[39] and better running form and running economy.[57]The extent to which these factors contribute to or mitigate against overuse injuries has been under intensive study in the last decade.

One reckons that from an evolutionary perspective, the most ‘natural’ way seems to be the barefoot way, and this has been backed up by the numerous studies indicating the deleterious effects of shoe wear especially in the pediatric population when the foot arch is developing. The advent of the modern running shoe in the 1970’s has been met with a persistence of running related overuse injuries.[11] A lot of research has been directed towards understanding the functional differences of the unshod versus shod foot, as well as unraveling the mystery of overuse injuries in the last three decades, but most of these studies focused on a **habitually shod population**.

A pertinent question therefore is: is the Western foot, used in most studies, not ‘natural’ any more, and is our current knowledge of foot biomechanics clouded by the effects of footwear – in other words, are we studying ‘deformed’, but not biologically ‘normal’ feet?

It is for this reason that this study set out to start filling the void by analyzing morphological foot arch characteristics in a population that seldom wears shoes. We are all aware that such a population is steadily becoming extinct with modernization, and such a comparison might not be possible in the near future.

CHAPTER THREE:

PROBLEM STATEMENT

It is not clear whether the habitually barefoot and habitually shod differ in foot structure and what factors account for these differences.

The incidence of running overuse injuries in the physically active in Kenya is unknown.

RESEARCH QUESTIONS

How comparable are the foot arch characteristics and lower limb overuse injury prevalence in the habitually barefoot and the habitually shod?

Are there other factors apart from the barefoot state that can contribute to arch strength and flexibility within the two groups, i.e. HB and HS?

OBJECTIVES

1. Measure the foot arch height and flexibility, intrinsic foot muscle strength and overuse injury incidence rates in the HB and HS and perform a comparative analysis between the groups.
2. Investigate the effects of gender and physical activity levels on foot strength and flexibility within the two groups, HB and HS.

Definitions of interest

Foot strength and flexibility in this study is indicated by intrinsic foot muscle strength and foot arch flexibility respectively.

JUSTIFICATION

Overuse injuries in the lower limbs are a concern to the child and adolescent athlete, contributing to a drop in sporting performance, loss or drop outs in competitive athletics seasons and loss of revenue or even worse, livelihoods for the career athletes. Western incidence rates stand at 20 to 80% per annum. The burden would probably be higher for our local non-elite athletes, who seldom have qualified running coaches to help prevent injuries during training, seldom have good medical covers that cater for their treatment needs and worse still, tend to over train in the hope of using their athletic endeavors as a ticket out of poverty.

Injuries also affect schooling activities due to time taken off for treatment and rehabilitation purposes. Overuse injuries may keep an athlete out of activity for a minimum of one week. Several injuries in a schooling term could thus easily lead to deterioration in school performance.

Majority of the completed and ongoing studies focus on the shoe wearing populations, and thus the findings could easily be biased. Till this work began, there had been no research on running related injuries or foot adaptations in the general Kenyan, and more specifically, the habitually barefoot population. The much we know is mostly anecdotal. Concerning our elite athletes, majority seek help overseas, denying us the opportunity to treat, rehabilitate and research. Further we know that most of our local elite athletes started off as barefoot runners and may well have benefitted from barefoot adaptations. That may explain their wining exploits especially in long distance events. It is thus paramount as researchers to re-focus our energies to barefoot populations, because such populations are becoming extinct with urbanization taking root in most of Africa.

CHAPTER FOUR: METHODOLOGY

4.1 STUDY SAMPLE, SITE AND POPULATION

76 subjects were selected for the study as follows:

38 (19 girls, 19 boys) habitually barefoot (HB) adolescents aged 12 to 18 years from Pemja Primary school (situated at an altitude of approximately 2400 m on the Nandi escarpment, South Nandi district, Kenya) participated in the study. They all took athletics as their favorite sporting activity, and were among the most physically active in their classes. A habitually shod group, 38 in number, who were age-, gender- and weight-matched children from Chebisaas Girls high school (Kobujoi, South Nandi district, Kenya), Mother of Apostles seminary secondary school and Kapsoya primary school (Eldoret town, Uasin Gishu district, Kenya)was selected. The habitually shod group either played soccer or practiced athletics actively.

The study compares the means of continuous variables in two independent populations. The formula for determining the sample sizes to ensure that the test has a specified power (80%) at 95% confidence level is

$\mathbf{n_i = 2\,(Z_{1-\alpha/2} + Z_{1-\beta})^2/ES}$ (Lisa M. Sulvan, 2003)[66]

Where $Z_{1-\alpha/2}$ is the value from the standard distribution (α-level of significance) and $Z_{1-\beta}$ is the power of the study.

ES is the effect size (Standard deviation/difference in means). From the pilot study, the effect size was 0.412

Thus $n= 2(1.96+0.84)^2/ 0.412 = 38.05$ per group. **Hence the total sample size is 76**

4.2 STUDY DESIGN

This was a cross-sectional study, with a retrospective analysis of lower limb overuse injuries.

4.3 EXPERIMENTAL DESIGN

a) Foot arch structural characteristics.

The arch height and relative arch deformity were used to characterize the medial longitudinal arch according to the protocols of Williams et al. and Zifchock et al.[58, 59] The following anthropometric measures were taken to arrive at the variables above:

Foot length - Length of the foot in the non-weight-bearing condition, from the most posterior aspect of the heel to the tip of the longest toe.

Dorsum height – Perpendicular height from the floor to the highest point on the dorsum of the foot at 50% foot length. This represented the arch height in this study.

Relative arch deformability (RAD) - Computed to characterize arch mobility/flexibility, it was calculated using an equation originally from Nigg et al.[60] and modified by Williams and McClay[59]:

$$RAD = \left(\frac{AH\ seated - AH\ standing}{AH\ seated} \right) \frac{10^4}{BW}$$

Where arch height (AH) is defined as dorsum height in seated and standing and body weight (BW) is expressed in newtons. Normal value according to Nigg et al.[60] is 1-2. A higher value signifies a more mobile arch.

The measurements were done in two conditions: seated and standing. Whereas radiographic measurements are the gold standard in determining the bony structure of the foot, and thus for arch quantification, many research laboratories do not have access to such methods.

This experimental setup was intended to be as simple and accurate as possible to allow for data collection in a rural setting, and so anthropometric quantification of the arch had to be employed. The methodology of arch height measurement was developed by Williams and McClain, using handheld calipers.[59]

Subjects were seated on a chair placed on a low table to ensure an even surface under the foot and allowing the foot arch to drop naturally. Knee and hip joints were held at 90 degrees flexion with the foot stably positioned on the horizontal surface. Total right foot length was measured in cm using a metal segmometer (Rosscraft, Canada). The foot dorsum height at 50% foot length was measured using an arch height index measuring system (AHIMS, see figure 1, appendix) which is a set of sliding calipers, that positions the measuring jaws both at half the foot length and highest point of the foot dorsum simultaneously. This was done in the seated position followed by a standing position. Measurements were taken by a single investigator, recorded in cm. The change in arch height between sitting and standing represents arch deformability due to the increased load.[58]

Other Anthropometric measurements

Height was measured by a tape measure with the subject comfortably standing upright against a vertical surface. Units of measure were metric, with rounding off to the nearest cm.

Body weight was measured to the nearest 100 g by a locally available electronic weighing scale (Salter 144SVBKDR, Salter Houseware Ltd. UK) while subjects were barefoot and wearing the school uniform.

Body mass index (BMI) was then computed from the above two measurements.

b) Intrinsic foot muscle strength.

The right foot, foot shortening strength was measured using a commercially available foot strength device (TKK 3360, Takei, Japan – see figure 2, appendix) while a subject was seated on a chair with the hip and knee joints at 90 degrees. In order to isolate the intrinsic muscles of the foot, the subject was required to passively invert and revert their foot so that a neutral position with respect to the subtalar joint would be attained. The subject was asked to perform plantar flexion of the 1st metatarsal against the strain gauge while maintaining the upright position of the toes, thus achieving approximation of the forefoot to the hind foot, or foot shortening.[61] The instructor stabilized the foot with the first metatarsal head on the metal rod and stabilized the heel against the heel cup to prevent a heel lift during the procedure. This movement was also demonstrated by the investigator severally to ensure the subject mastered it. Three trials were performed with each test and the best or highest reading result recorded. Measurements were taken by a single investigator. The strain gauge was calibrated in kilograms.

c) Overuse Injury Incidence.

Standardized questions regarding lower limb injuries were asked, seeking to diagnose overuse injuries for a period of one year up to the time of interview. Foot deformities were also sought for by a resident orthopaedic surgeon (PO). Diagnoses were based on the International Classification of Disease, 9th Revision, Clinical Modification (ICD-9-CM). The clinician conducted a self-directed learning of overuse injuries beforehand to optimize standardization of the diagnoses. Overuse injuries were defined as musculoskeletal problems of insidious onset associated with repetitive physical activity. The following common injuries were sought for: plantar fasciitis, Achilles tendinitis, medial tibial stress syndrome, patellofemoral pain syndrome and iliotibial band syndrome.

An injury was considered significant if it was severe enough to prevent full participation in normal physical activities for at least one week. Stress fractures were omitted due to the potential diagnostic difficulty in the rural study site.

d) Physical activity level assessment.

Physical activity levels and patterns were objectively measured in 31 subjects randomly selected from the entire study group for 6 consecutive days during school term time using the ActiTrainer uni-axial accelerometer (ActiGraph LLC, Pensacola, FL, USA) worn with a Velcro belt around the waist according to the recommendations of the manufacturer. The sub selection was done due to the limited number of accelerometers. Each subject was instructed to wear the device at all times except when sleeping and bathing. The recording epoch was set at 60 s. Ojiambo et al[45] have shown that group differences in moderate to vigorous physical activity can be demonstrated with 60 s epoch although some differences – Moderate to vigorous physical activity(MVPA) in very short bouts – would be lost. An epoch of 15 to 30 seconds, though, is considered ideal for younger age groups. The monitoring of physical activity levels was considered valid for inclusion in the analysis if a minimum of 12 h of recordings took place per day for at least 3 days (including at least one weekend day). The same authors have demonstrated that minimum acceptable reliability can be obtained with 3 days. It should be noted, however, that most of the subjects in this study had considerably more than 3 valid days of measurement. Accelerometer data were analyzed using algorithms developed by Ojiambo et al.[45] The measurable outcome was the moderate to vigorous physical activity (MVPA), as a percentage of the entire measured physical activity.

4.4 STATISTICAL ANALYSIS

Means and standard deviations of continuous variables, such as body height, body weight, were calculated. Comparison between HB and HS subjects were performed using the wilcoxon Mann-Whitney U-test with the p value set at 0.05, to determine whether differences in foot structure characteristics existed between these groups. Accelerometer data were analyzed using algorithms developed by Ojiambo et al.[45] The injury prevalence was calculated by dividing the number of injuries by the total number of subjects studied, and significance calculated by the chi-square test. Co-variant analysis was done using Spearman's test to find out correlation between the various variables measured.

4.5 STUDY LIMITATIONS:

1. Study group chosen i.e. the habitually barefoot is restricted in both age and occupation – school children. Hence the findings may not be totally representative of the whole athletically active barefoot population.
2. Whereas it would have been desirable to interrogate the injury data further, the relatively few injuries diagnosed due to the limited sample size does not allow correlation analyses between this and various measured foot structural variables. Hence the study remains mostly descriptive in as far as injury data is concerned.
3. Budgetary and time constraints determined the study design. A cross sectional and retrospective survey rather than a prospective study had to be conducted, whereby it would have been desirable to select study groups into cohorts according to selected risk factors then follow them over time for occurrence of outcomes of interest.

4.6 ETHICAL CONSIDERATIONS

In order to protect and respect the rights of the participants who took part in the study, the following steps were taken.

1. Permission and clearance to conduct the study was sought from the Institutional Research Ethics Committee, Moi University Eldoret, Kenya. (IREC).

2. To ensure confidentiality and privacy of the study subjects, each subject was given a code that was used on the checklist and thus names were not used. The code was only known by the participants and researcher.

3. Because of age of the participants, two consent forms were designed, one for the teachers and the other for the parents/guardians - which was to be signed by the teachers on their behalf. There was an information document entailing the details of the experiments and the teachers only signed consents having read and understood this document.

4. It was made clear that enrolment into the study would be voluntary with no monetary or material gains expected.

5. Study subjects had an option to withdraw from the study at any given time upon communication with the principal investigator.

CHAPTER FIVE: RESULTS

A. Subject demographic and anthropometric characteristics: The ages and physical characteristics of the subject population are presented in Table 1. Both groups were gender, age and weight matched but HB adolescents were taller and had a significantly lower body mass index (BMI).

Table 1: Table of subject`s demographic and anthropometric characteristics

Mean + SD and range are presented.

	Subjects (n)	**Age (years)**	**Height (cm)**	**Weight (kg)**	**BMI (kg/m^2)**
HB	38	15.1 ± 1.4	162.3 ± 9.0	44.9 ± 7.4	17.0 ± 2.0**
	(19 b; 19 g)	12 – 18	142 - 177	27 - 61	13.1 – 21.4
HS	38	15.1 ± 1.4	157.9 ± 9.6	45.3 ± 6.9	18.2 ± 2.1
	(19 b; 19 g)	12 – 18	140 - 180	27 - 61	13.7 – 24.9

Note: HB – habitually barefoot group; HS – habitually shod group; BMI – body mass index,
b – boys; g – girls; * $p<0.05$ ** $p<0.01$

Ethnicity of the study group

All the habitually barefoot came from the kalenjin community while 7/38(18%) of the habitually shod came from other communities including Kikuyu, Kisii and Luhya.

In total, 69/76(91%) were Kalenjin against 7/76(9%) from other communities.

B. Foot arch height, flexibility and intrinsic foot muscle strength.

Foot flexibility, intrinsic foot muscle strength and arch height are represented by RAD, IFM strength and foot dorsum height respectively in table 2. The means, range of the values, Z and P values are presented.

Table 2: Foot arch height, flexibility and intrinsic foot muscle strength in the habitually barefoot and habitually shod.

Arch characteristic	**Group**		**Z-value**	**P-value**
	HB	**HS**		
Relative arch deformability, (RAD)	**0.775(0.583, 1.063)**	0.635(0.408,0.778)	-2.520	0.012
IFM strength (kgs)	**4.700(3.100, 6.125)**	3.300(2.175, 4.350)	-2.962	0.003
Foot dorsum height	**6.7(5.6, 8.1)**	6.2(4.6, 7.2)	-2.520	0.010

HB – habitually barefoot; HS – habitually shod

The wilcoxon Mann-Whitney U-test indicated that there was a significant difference in the mean relative arch deformability, (RAD) intrinsic foot muscle strength (IFM strength) and arch height between habitually barefoot and habitually shod children/adolescents (p=0.012, 0.003 and 0.010) respectively. The habitually barefoot exhibited higher, more flexible arches and stronger intrinsic foot muscle strength compared to the habitually shod group.

C. Lower limb overuse injury incidence.

Presented in table 3 are the frequencies and incidence rates(in brackets) of the lower limb overuse injuries in the habitually barefoot and habitually shod. Also presented is the incidence and of buinions.

Table 3: Incidence and incidence rates of the diagnosed lower limb overuse injuries and foot deformity.

Injury	**HB**	**HS**
Plantar fasciitis	1(2.6%)	5(13.1%)
Achilles tendinitis	0	1(2.6%)
MTSS	0	1(2.6%)
PFP	0	3(7.9%)
ITBS	0	1(2.6%)

Chi-square =9.896, p<0.002

HB – habitually barefoot; HS – habitually shod; MTSS – medial tibial stress syndrome; PFP – patellofemoral pain; ITBS – Illiotibial band stress

Buinions	**HB**	**HS**
Yes	0	5
No	38	33

Chi-square =17.049, p<0.001

As indicated in table above, there was only 1(2.6%) injury in the habitual barefoot group compared to 11(28.8%) in the habitual shod group. The difference in the number of injuries was significant (Chi-square =9.896, p<0.002)

Plantar fasciitis was the commonest diagnosed overuse injury, with an overall incidence rate of 14.7% in the entire study group.

The HS group likewise manifested a higher incidence of bunions; 13.6% versus 0% in HB.

Overall incidence rate of overuse injuries was 31.4%.

D. Gender variations in foot arch flexibility and intrinsic foot muscle strength.

Presented in table 4 is foot arch flexibility and intrinsic foot muscle stength of the study group, stratified according to gender. The means, range, Z and P values are shown.

Table 4: Correlation between gender and foot arch flexibility, intrinsic foot muscle strength.

Arch characteristic	**Habitually barefoot**		**Z-value**	**P-value**
	Male	**Female**		
Relative arch deformability, (RAD)	0.730(0.520, 1.060)	0.780(0.660,1.140)	-0.745	0.456
IFM strength	4.700(3.300, 6.200)	4.5(3.100, 5.600)	-0.424	0.672
Habitually shod				
Relative arch deformability, (RAD)	0.56(0.400, 0.870)	0.650(0.410, 0.760)	-0.219	0.827
IFM strength	3.300(1800, 4.000)	3.70(2.300, 4.500)	-0.877	0.381

The wilcoxon Mann-Whitney U-test indicated that there was no significant difference in the mean Relative arch deformability, (RAD) and intrinsic foot muscle strength between the genders in habitually barefoot and habitually shod adolescents (p>0.05).

E: Physical activity levels, foot arch flexibility and intrinsic foot muscle strength in the HB and HS.

Presented in table 5 is the correlation between physical activity level and foot arch flexibility, intrinsic foot muscle strength. The spearman coefficient values and the p values are shown.

Table 5: Correlation between physical activity level and foot arch flexibility, intrinsic foot muscle stength.

Arch characteristic	**Activity level (MVPA%)**
Relative arch deformability, (RAD)	rho=0.332 (p=0.068)
IFM strength	rho=0.150 (p=0.420)

Using the spearman correlation (rho), no significant correlation was observed between relative arch deformability, (RAD) and intrinsic foot muscle strength and measured physical activity among the tested group.

CHAPTER SIX: DISCUSSION

A. Foot Arch Characteristics

1. Arch height

The core results demonstrated significant differences in the measured foot arch characteristics between the groups. The habitually barefoot in this study exhibited **higher arches** compared to the habitually shod. Barefoot activities during the first years of life could be the reason for the proportional increase in the height of the medial longitudinal arch of the foot in this study. These findings are similar to those of Echarri et al [22].Williams et al.[8] divided runners in to high arched and low arched according to arch ratio. They defined arch ratio - similarly to this study - as the height to the dorsum of the foot at 50% of the foot length divided by truncated foot length. They considered the arch high with the arch ratio of at least 0.356 and the arch to be low with the arch ratio of at the most 0.275. According to the arch ratio parameters in the Williams study, the subjects in this study could be classified as high arched in HB with arch ratio 0.40 ± 0.04 seated and 0.39 ± 0.04 standing and normal to high arched in HS with arch ratio 0.36 ± 0.03 seated and 0.35 ± 0.03. Studies done in the past show variable results in so far as arch height is concerned. The study by D'Août et al.[62] in 2009 bears the closest resemblance to this study in terms of design, having investigated a habitually barefoot Indian population and compared this to both a habitually shod Indian and thirdly, a Belgian (western) population. Metric measurements of the navicular height and navicular drop were taken with a caliper, as well as estimation of the relative plantar weight bearing surface area. Their results indicated that the barefoot and shod Indian population had relatively low or low normal arches whereas the western population had variable arch heights, either very high or very low. They however don't explain their arch classification. They also concluded that barefoot walkers had wider feet compared to the shod, signifying a more uniform distribution of plantar pressures.

Echarri and Forriol,[22] Rao and Joseph[23]both demonstrated that flat footedness (very low arches) in the habitually shod populations was associated with use of constrictive shoe wear in childhood.

2. Arch flexibility

This study demonstrated a **greater arch deformation** in the habitually barefoot compared to the habitually shod. This indicates **greater arch flexibility** in these children. Arch flexibility has been biomechanically related to hindfoot motion.[63] A more flexible arch means greater evertion excursion of motion at the subtalar joint and this has been positively correlated with greater protection against overuse injuries.[51] Thus more flexible arches could potentially be linked to less overuse injuries. Kadambande et al.[26] compared a habitually barefoot Indian population sample and a habitually shod British group. They utilized a pliability ratio to measured splaying of the foot during weight bearing in the two groups. They found out that the barefoot population had significantly pliant feet.

To the best of the researcher's knowledge, this is the first study to document higher and more flexible arches in the habitually barefoot population. Most of the documented studies including the one by Williams et al[8] found an inverse relationship between arch height and flexibility, with the high arched tending to have stiffer arches and the low arched more flexible arches. The reason, as highlighted before could be the difference in shoe wearing lifestyles between most studies and this. It has been shown by Prince et al. that arch stiffness is dependent on age, with the older age groups tending to have stiffer arches.[43]This study has been able to demonstrate variability in arch stiffness from a population with a similar age cohort. It is important to point out the difficulties in comparing data concerning foot arches because of the different methods in its characterization. There has been no standardized protocols, with majority of earlier authors using qualitative descriptions,[2, 3, 4, 5] others footprint analysis[7] and more lately anthropometric and digital photographic methods.[58, 59]

The relative arch deformation in the HB was much greater in this study compared to Williams and McClay[59] probably due to greater barefoot adaptations involving the intrinsic structures of the foot; higher activity of intrinsic muscles of the foot maintaining a high arch height in non-weight bearing conditions, as well as a better dynamic support via eccentric contraction to allow a controlled yet greater arch collapse during weight bearing conditions.

The body mass and body mass index are important factors to determine for assessing foot arch characteristics like flexibility. It is noteworthy that subjects in the current study were weight-matched. Studying subjects with similar body mass was intentional, since it was believed that the load of larger or smaller body mass on the measured foot arch indices would have influenced the characteristics measured. It has previously been found that body mass is positively correlated to arch height.[8] In the Williams study on runners aged 28 ± 8 yrs., average body weight was 6.28 kg lighter in the high-arch group than that in the low arch group. With regards to age, the subjects of the Villarroya et al. study of foot structure and obesity are more comparable with the subjects in this study.[64] They studied 245 children in the age 9 – 16.5 and correlated the arch height with their BMI. The obese and overweight children had significantly lower arches compared to normal weight children.

3. Intrinsic foot muscle strength

One of the hypotheses of this study was that a habitually barefoot lifestyle develops and strengthens intrinsic foot muscles. Intrinsic foot muscles assist actively in controlling medial longitudinal arch collapse depending on the load exerted and the body`s movements. The current study indicated significantly greater foot shortening strength. The more ‘arch-mobile’ foot in HB would be stabilized by stronger muscles when pronation control is required resulting in less strain being placed on the soft tissue structures such as ligaments and tendons. As EMG of the intrinsic and extrinsic foot muscles was not measured, the amount of work done by the calf muscles cannot be determined. However, according to Jung,[65] in foot shortening exercise, the abductor hallucis activity was 45.2% of the muscle maximum voluntary isometric contraction. This study found intrinsic foot muscles to be stronger in HB compared to HS.

These results are supported by the static footprints study conducted by Rao and Joseph who found a higher prevalence of flat feet in shod children compared to habitually barefoot children in India, and they attribute this finding to the type of footwear habitually barefoot children wore, which influenced the development of longitudinal arch of the foot,[23] They suggested that children who wore slippers or sandals were activating the intrinsic muscles in the foot more in order to keep the slippers on the feet. In this study, habitually barefoot children reported to use mainly rubber slippers if they had to wear some shoe, especially on Sundays for attending worship or whenever they visited a big town like Eldoret or Kisumu. Further, a longitudinal study conducted by Potthast et al. indicated the greatest growth of the anatomical cross sectional areas of m. flexor hallucis longus, m. abductor digiti minimi, m. quadratus plantae and m. abductor hallucis over the period of 5 months of wearing minimal footwear,[41] They concluded that training in minimal footwear induces mechanical stimuli leading to bio positive adaptation. This study's findings suggest that the barefoot state in the subjects would induce even greater adaptations.

Ethnicity and arch structure

In this study, 69/76(91%) were Kalenjin against 7/76(9%) from other communities. With the entire group considered together, their mean arch height index (0.36±0.2) would be considered high normal according to the Williams et al arch parameters.[8] Genetic predisposition has been described in bilateral non-pathological flat footeedness.[23, 24] To the best of the researcher's knowledge, no genetic predisposition has been described in non-pathologic high foot arches.

B. Overuse injury and foot deformity incidence.

The analysis on injuries placed the overall incidence of overuse injuries at 31.4%. This is comparable to previously reported incidence rates, with the systematic review by Gent et al. of 2007 placing this between 19.4% and 79.3%.[11] A possible explanation of the relatively low incidence is the almost virtual absence of injury in the habitually barefoot group, with only one case of plantar fasciitis diagnosed. Further, the injuries were diagnosed retrospectively and there could have been a recall bias. This dropped the overall incidence rate tremendously. Secondly, the study population partakes in athletic and sporting activities only during class time breaks, games time and over the weekend whereas data from the west was collected mainly from career athletes during competitive season and recreational athletes.

Whereas the commonest overuse injury in many reports[10, 11] is anterior knee pain (patellofemoral syndrome), the commonest injury in this study was plantar fasciitis.

There was a comparatively higher incidence of foot deformity, in this case bunions in the habitually shod. This has been noted by several authors[2, 5] and the main explanation is wearing of constrictive shoes with a narrow toe box. The effect is maximal when the onset of wearing such footwear is during foot arch development in early childhood.[7]

C. **Other factors affecting arch structural characteristics**

The level of physical activity was objectively measured with uni-axial accelerometry. The percentage of active time spent in performing moderate to vigorous activity was measured. There was a weak positive correlation found between physical activity levels and foot arch flexibility, and no correlation between activity and foot muscle strength. It is however noteworthy to acknowledge the lack of sufficient numbers of subjects in the study in whom accelerometry was carried out. Nevertheless, the weak positive correlation found would indicate the need for a larger sample size on which accelerometry needs to be conducted to analyze the effect of physical activity on foot structural adaptations.

Correlation analysis of gender versus arch characteristics also failed to yield any significant relationships. Hence this remains an open area for further research.

CHAPTER 7:

CONCLUSIONS

The study compared a habitually barefoot and a habitually shod population sample of Kenyan adolescents of both sexes. The habitually barefoot exhibited the following;

- **Higher and more flexible foot arches**
- **Stronger foot intrinsic muscles**
- **Lower incidence of lower limb overuse injuries**
- **No correlation between gender, activity levels and foot arch characteristics**

RECOMMENDATIONS

- Integration of foot strengthening strategies in our rehabilitation and treatment plans of chronic activity related foot pain.
- Barefoot training regimes to be developed and taught to our local athletics coaches to improve foot health.
- Further prospective studies need to be conducted to correlate the overuse injuries and foot structure.
- Further investigations to look into the relationship between physical activity and foot form in both the habitually barefoot and habitually shod.

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APPENDICES:

APPENDIX 1:

ARCH HEIGHT INDEX MEASURING SYSTEM (AHIMS)

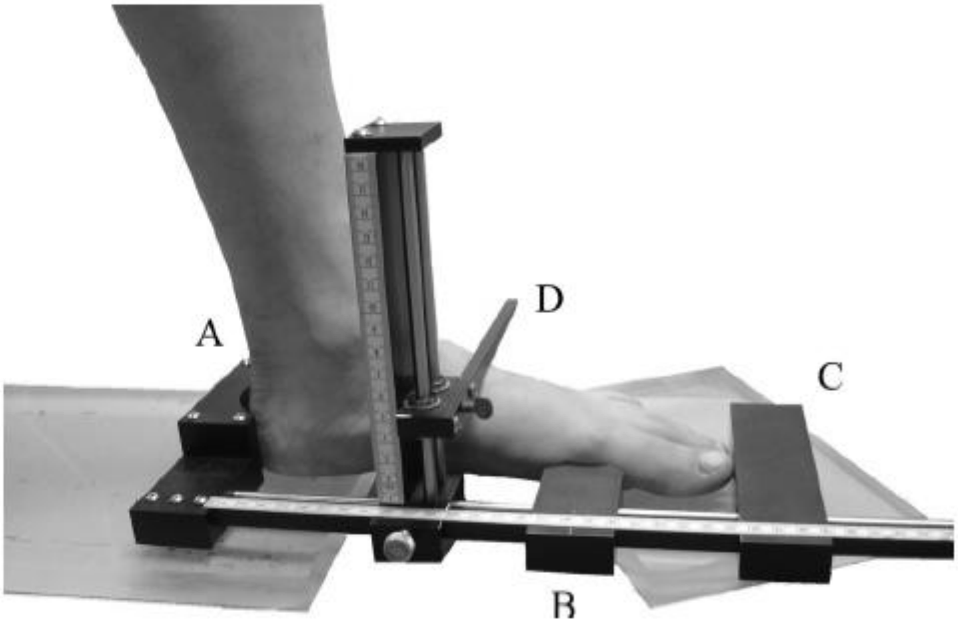

Fig. 1: The Arch Height Index Measurement System (AHIMS). This figure shows only the left foot apparatus. Platforms are placed under the heel and metatarsal heads of each foot, leaving the midfoot unsupported. When the AHIMS is properly aligned, the posterior heel is flush with the heel cup (**A**), the sliding hemispherical recess is positioned against the first metatarsal joint (**B**), the sliding toe bar rests gently against the longest toe (**C**), and the drop bar rests against the dorsal surface at half the total foot length (**D**).

Zifchock et al. 2006[58]

Figure 1: The arch height index measuring system.

APPENDIX 2: FOOT STRENGTH MEASURING DEVICE

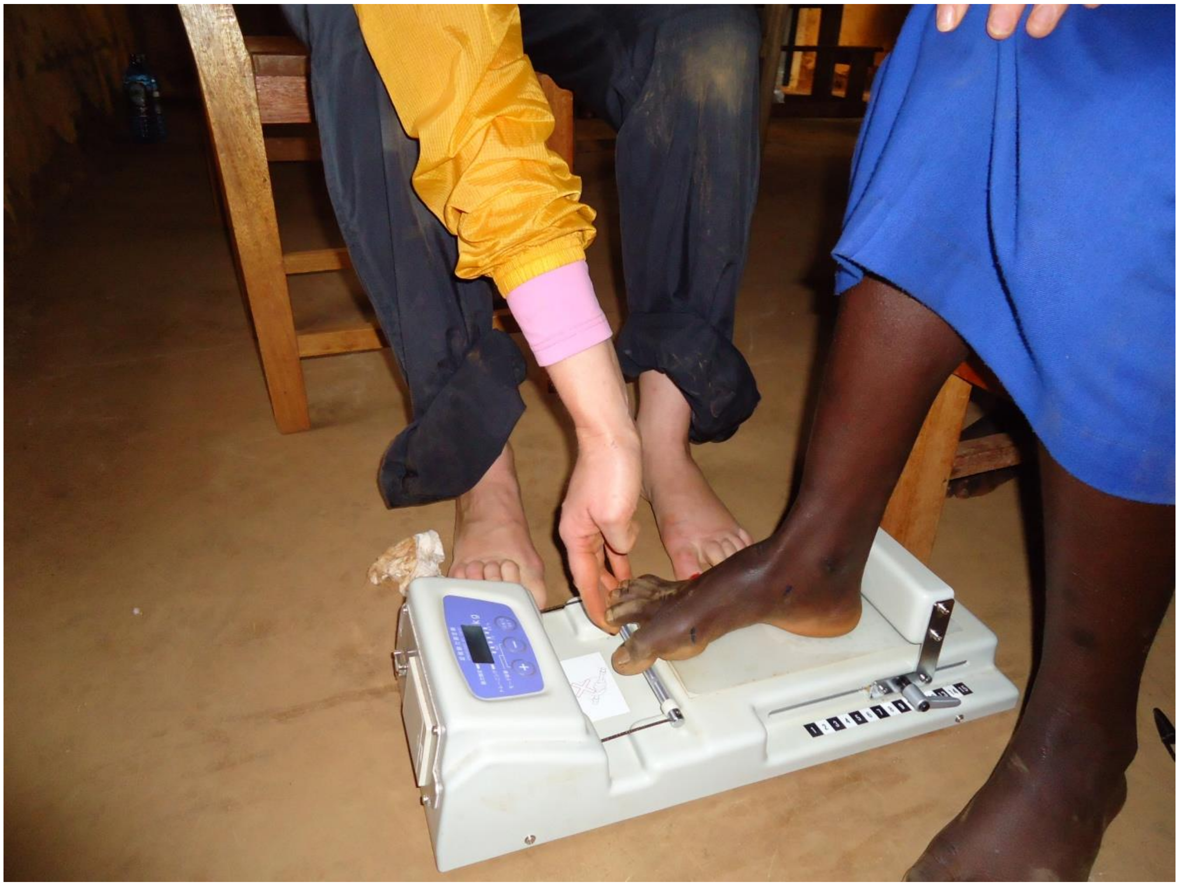

Figure 2: Foot strength measuring device.

APPENDIX 3: IREC APPROVAL

INSTITUTIONAL RESEARCH AND ETHICS COMMITTEE (IREC)

MOI TEACHING AND REFERRAL HOSPITAL
P.O. BOX 3
ELDORET
Tel: 33471//2/3

MOI UNIVERSITY
SCHOOL OF MEDICINE
P.O. BOX 4606
ELDORET
Tel: 33471/2/3

Reference: IREC/2011/115

1st September, 2011

Approval Number: 000695

Dr. Paul Makokha
Moi University
School of Medicine
P. O. Box 4606 - 30100
ELDORET, KENYA

Dear Dr. Makokha

RE: FORMAL APPROVAL

The Institutional Research and Ethics Committee have reviewed your research proposal titled:

"A comparison of bioenergetics in unshod habitual barefoot runners and a profile of their foot arches"

Your proposal has been granted a Formal Approval Number: **FAN: IREC 000695** on 1st September, 2011. You are therefore permitted to begin your investigations.

Note that this approval is for 1 year; it will thus expire on 31st August, 2012. If it is necessary to continue with this research beyond the expiry date, a request for continuation should be made in writing to IREC Secretariat two months prior to the expiry date.

You are required to submit progress report(s) regularly as dictated by your proposal. Furthermore, you must notify the Committee of any proposal change (s) or amendment (s), serious or unexpected outcomes related to the conduct of the study, or study termination for any reason. The Committee expects to receive a final report at the end of the study.

Yours Sincerely,

02/09/2011

INSTITUTIONAL RESEARCH & ETHICS COMMITTEE
APPROVED
01 SEP 2011
P.O. Box 4606 ELDORET

DR. W. ARUASA
AG. CHAIRMAN
INSTITUTIONAL RESEARCH AND ETHICS COMMITTEE

cc:	Director	-	MTRH
	Dean	-	SOM
	Dean	-	SPH
	Dean	-	SOD