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Physical efficiency as a function of age: Development of an age scaling model for biomechanical simulation

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Abstract

Background: There have been drastic changes in demography in the past 50 years in terms of population rise combined with a change in the age composition. Aging in general causes a decline in strength and flexibility of the body. Given these factors, it is becoming more and more important to provide support to the aging population in terms of evaluation and design of comfortable and safe environments at work and during activities of daily living. In today's state-of-the-art technology, digital human modeling is proving to be a useful and valuable simulation tool for ergonomics. A relatively new DHM called the AnyBody Modeling System^{TM} or AMS that functions on the principle of inverse dynamics has been developed by an interdisciplinary group at Aalborg University in Denmark. This system differs from most of its predecessors because it is a sophisticated musculoskeletal mannequin comprising several hundred muscles rather than an enveloped volume-based mannequin. In order that a model be useful in ergonomics, work place evaluation and product design in general, it is vital that it is scalable. Scaling alludes not only to anthropometry or percentile scaling of the human body, but also to age and gender. The scaling algorithms in AMS lack the input of age and gender as well as the option to scale different functional muscle groups differently.

Objectives: The goal of the project is to develop a law that scales the maximal voluntary isometric contraction of the knee extensors and elbow flexors of males and females aged 50 to 79 years based on the following variables: body part, age, gender, height, body mass, segment length, segment mass. Two methods are used for this purpose: Multiple Linear Regression (MLR) and a nonlinear programming technique called Cumulative Approximation (CA). The equations are then reduced to a set of necessary dependencies by removing redundancies based on multicollinearity. Results of both methods are statistically analysed and validated in AMS. The hypothesis of the validation in AMS is that the age-gender strength scaled equations should be closer to the true measured strength than the strength predicted by the AnyBody length-mass-fat scaling law.

Methods: The age groups were divided decade-wise i.e. 50-59, 60-69 and 70-79 years with approximately 50 males and 50 females per group. Subjects were externally and internally recruited from all walks of life. A subjective pain and physical activity questionnaire was obtained. 3-D total body scans in standard and customised postures were performed using optical triangulation or laser technology (Model Vitus SMART, Human Solutions GmbH, Kaiserslautern, Germany) to determine the anthropometric measurements in accordance with the ISO 20685 standard. Peak torque was measured during a maximal voluntary isometric contraction of the right knee extensors and right elbow flexors using the IsoMed 2000 dynamometer (D&R Ferstl GmbH, Germany).

Analysis: The customised bodyscan was used to calculate the segment masses. Exploratory data analysis was carried out to examine each of the six groups for normality. Factor analysis was used to investigate underlying relationships between variables. MLR analysis was performed to establish separate strength scaling equations for the elbow and knee. Statistical redundancies were removed to create a simplified equation of necessary and sufficient dependencies. CA technique was also used to investigate strength scaling equations. In order to assess the knee and elbow models, two forms of cross-validation were employed: 2-fold and leave-one-out method. The scaling equations were then validated in AMS and compared with the latest scaling equation available in AMS.

Results: Males have significantly higher strength than females across all age groups, and for both elbow and knee strength. The elbow peak torque of the youngest males and youngest females are significantly higher ($P<0.05$) than the two older age groups. Knee peak torque significantly decreases ($P<0.05$) across all three age groups, for both genders. Factor analysis clustered the data into three sets: gender and lengths explaining circa 50%; masses explaining 16%; and age explaining about 12% of the variance in strength. The optimal model for MLR analysis of the elbow was explained by gender, forearm mass and age where the explained variance R^2 was 74%. In terms of the knee, this was optimally explained by age, thigh mass and gender with an explained variance of 61%. The CA models based on the same dependencies as MLR models explained 72% and 36% variance of upper and lower limb strength respectively. The hypothesis of validation in AMS is true for both elbow and knee models for 74% and 69% of the subjects respectively.

Conclusion: A major finding of this study supports the basic research hypothesis that using MLR, it was possible to reduce the predictors of isometric peak torque from eight variables to three including gender, one segment mass and age. The two-fold and leave-one-out methods established a high degree of cross-validation in both models. The second important result of this study is that contrary to the initial hypothesis, CA did not produce a more accurate prediction of strength compared to MLR. The answer to the third hypothesis is that the age-gender strength scaling laws provided a much more accurate strength prediction than the existing scaling laws in AMS, ranging from a few percent to as high as 45%. This study provides a database of anthropometry and strength of a representative sample of the older population of Munich. Two reduced strength scaled equations of the lower and upper body, based on age and gender have been presented to further improve the accuracy of strength scaling in AMS.

Abstract in German

Hintergrund: In den vergangenen 50 Jahren gab es drastische demographische Veränderungen in Form eines Bevölkerungsanstiegs und einer geänderten Alterszusammensetzung. Alterung verursacht im Allgemeinen einen Rückgang der Körperkraft und Flexibilität. Angesichts dieser Tatsachen wird es immer wichtiger, die alternde Bevölkerung bei der Arbeit und alltäglichen Aktivitäten durch Auslegung und Gestaltung von ergonomischen Umgebungsbedingungen zu unterstützen. Dank modernster Technologien stellt die digitale Modellierung des menschlichen Körpers digitales Menschmodell ein nützliches und wertvolles Werkzeug zur Steigerung der Ergonomie dar. Ein vergleichsweise neues digitales Menschmodell ist AnyBody Modeling System^{TM} oder AMS. Es basiert auf der Grundlage von inverser Dynamik und wurde von einem interdisziplinären Forscherteam der Aalborg Univerität in Dänemark entwickelt. Dieses System unterscheidet sich von den meisten seiner Vorgänger dadurch, dass es ein Muskelskeletmodell mit einen komplexen Bewegungsapparat aus mehreren hunderten Muskeln darstellt. Damit ein Modell nützlich für ergonomische Betrachtungen, Arbeitsplatzanalysen und Produktgestaltungen ist, muss es zwingenderweise skalierbar sein. Skalierung bezieht sich hierbei nicht nur auf die Abmessungen des menschlichen Körpers, sondern auch auf Alter und Geschlecht. Den Skalierungsalgorithmen von AMS fehlen jedoch die Eingabeparameter "Alter" und "Geschlecht", sowie die Möglichkeit, verschiedene funktionale Muskelgruppen auf unterschiedliche Art und Weise zu skalieren.

Ziele: Ziel dieser Arbeit ist es, ein Gesetz zu entwickeln, dass die maximale isometrische Kontraktion der Knie-Strecker und Ellbogen-Beuger von Männern und Frauen zwischen 50 und 79 Jahren auf Basis folgender Variablen ermittelt: Körperteil, Alter, Geschlecht, Körpergröße und -Gewicht, Segmentlänge und -Gewicht. Zwei Methoden werden zu diesem Zweck verwendet: Mehrfachregression (MLR) und eine nichtlineare Programmiertechnik namens kumulative Annäherung. Die Gleichungen werden dann auf die Menge der erforderlichen Variablen reduziert, indem Redundanzen auf Basis von Multikollinearität entfernt werden. Die Ergebnisse beider Methoden werden statistisch analysiert und in AMS validiert. Dabei besteht die Hypothese, dass die durch Alter und Geschlecht skalierten Gleichungen näher an den tatsächlich gemessenen Kräften liegen als die ausschließlich über Größe-Gewicht-Fett skalierten.

Vorgehensweise: Die Altersgruppen wurden in Jahrzehnte unterteilt, d.h. 50-59, 60-69 und 70-79 Jahre, mit annäherungsweise 50 Männern und 50 Frauen je Gruppe.

Probanden wurden vorwiegend auf öffentlichen Plätzen angeworben. Ein subjektiver Fragebogen zu Schmerzen und körperlicher Aktivität wurde erhoben. 3-D Ganzkörper-Scans in angewiesenen Messhaltungen wurden angefertigt. Mit Hilfe von optischer Triangulierung mit Lasertechnik (Model Vitus SMART, Human Solutions GmbH, Kaiserslautern) wurden die anthropometrischen Maße gemäß des ISO 20685 Standards ermittelt. Das maximale isometrische Drehmoment wurde mit dem IsoMed 2000 Dynamometer (D&R Ferstl GmbH, Deutschland) bei einer maximalen freiwilligen Anspannung des rechten Knie-Streckers und Ellbogen-Beugers ermittelt.

Analyse: Der angepasste Körper-Scan wurde dazu verwendet, die Segment-Gewichte zu berechnen. Eine explorative Datenanalyse wurde ausgeführt, um jede der sechs Gruppen nach Normalität zu untersuchen. Eine Faktorenanalyse wurde eingesetzt, um grundlegende Abhängigkeiten zwischen den Variablen zu ermitteln. Eine MLR-Analyse wurde durchgeführt, um separate Stärken-Skalierungs-Gleichungen für den Ellbogen und das Knie zu bestimmen. Nun wurden statistische Redundanzen entfernt, um vereinfachte Gleichungen mit allen notwendigen und ausreichenden Abhängigkeiten zu erhalten. Neben der MLR-Analyse wurde auch die kumulative Annäherung verwendet, um Stärke-Skalierungs-Gleichungen zu ermitteln. Um die Knie- und Ellbogen-Modelle zu bewerten, wurden zwei Arten der Vergleichsprüfung eingesetzt: Die zweifache Kreuzvalidierung und die Leave-One-Out-Kreuzvalidierung. Die Skalierungs-Gleichungen wurden anschließend in AMS validiert und mit den aktuellen Skalierungs-Gleichungen von AMS verglichen.

Ergebnisse: Männer sind signifikant stärker als Frauen, und zwar über alle Altersgruppen hinweg sowohl im Ellbogen als auch im Knie. Das maximale Ellbogen Drehmoment der jüngsten Männer und Frauen ist signifikant höher ($P<0.05$) als das der beiden älteren Altersgruppen. Das maximale Knie Drehmoment nimmt für beide Geschlechter signifikant über all drei Altersgruppen ab ($P<0.05$). Die Faktorenanalyse unterteilte die Daten in drei Mengen: Geschlecht und Länge bestimmen etwa 50%, Gewicht etwa 16% und Alter etwa 12% der Varianz der Stärke. Das beste Modell der MRL Analyse des Ellbogens basierte auf den Variablen Geschlecht, Gewicht des Unterarms und Alter, wobei die erklärte Varianz R^2 74% betrug. Beim Knie waren es Alter, Gewicht des Oberschenkels und Geschlecht bei einer erklärten Varianz von 61%. Die kumulative Annäherung basierte auf den gleichen Variablen und erklärte 72% respektive 36% der Varianz der oberen und unteren Gliedmaßen. Die Hypothese der Validierung in AMS betreffend des Ellbogen- bzw. Knie-Modells ist für 74% bzw. 69% der Probanden gültig.

Fazit: Ein wesentliches Ergebnis dieser Studie unterstützt die grundlegende Forschungshypothese, dass es anhand der MLR Analyse möglich ist, die Prädiktoren der maximale Drehmoment von acht auf die drei Variablen (Geschlecht, Gewicht eines Körpersegments und Alter) zu reduzieren. Die zweifache Kreuzvalidierung und die Leave-One-Out-Kreuzvalidierung zeigen ein hohes Maß an Übereinstimmung beider Modelle. Das zweite wesentliche Ergebnis dieser Studie ist, dass, entgegen der Ausgangshypothese, die kumulative Annäherung im Vergleich zur MLR Analyse keine genauere Vorhersage für die Stärke liefert. Die Antwort auf die dritte Hypothese lautet, dass die auf Alter und Geschlecht

basierenden Skalierungsgesetze für die Stärke ein viel genaueres Ergebnis liefern als die bestehenden Gesetze in AMS, wobei die Unterschiede von wenigen Prozent bis hin zu 45% variieren. Diese Studie liefert eine anthropometrische Datenbasis der Stärke für eine repräsentative Stichprobe der älteren Bevölkerung Münchens. Es wurden zwei vereinfachte Gleichungen zur Vorhersage der Stärke des Ober- und Unterkörpers vorgestellt welche auf Alter und Geschlecht basieren und die Genauigkeit der Stärkenskalierung in AMS verbessern.

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I dedicate this dissertation to the most influential people in my life: my mother and father.

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Nomenclature

AMS	AnyBody Modeling System^{TM} , page 5
ANN	Artificial Neural Network, page 32
BMI	Body Mass Index, page 9
CA	Cumulative Approximation, page 31
CSA	Cross Sectional Area, page 9
DHM	Digital Human Model, page 5
EMG	electromyography, page 9
F/E	flexion/extension, page 9
FMG	Functional Muscle Group, page 9
MLR	Multiple Linear Regression, page 31
MVC	Maximum Voluntary Contraction, page 9
PT	Peak Torque, page 9
R^2	explained variance, page 44
SD	Standard Deviation, page 30
VIF	Variance Inflation Factor, page 44
ab/ad	abduction/adduction, page 9
df/pf	dorsiflexion/plantarflexion, page 9
r	Pearson's correlation coefficient, page 28

1

Introduction

"*Although it is known that strength declines with age, there is no agreement on how rapid this change is, whether the change is linear or curved or whether the changes differ with men and women*" (Chaffin 2001). This statement summarizes quite well the fundamental motivation behind this project. The introduction to this report starts off by providing insight into the changing demographics and the increasing need to provide more and more support for the aging population. This is followed by looking into the physiological effects of aging and the various types of muscular strengths. Next we introduce digital human models and focus specifically on the Anybody model, its working and the different types of strength scaling laws it has to offer. The general focus of the project is then discussed followed by the outline of the dissertation.

1.1 Changing demography

There have been drastic changes in demography in the past 50 years. In 1950, the world population was estimated at 2.5 billion whereas in 2011, our planet's 7th billion person was born. This number is predicted to increase to 9.1 billion by 2050 (UN 2007). Asia is by far the most populous area and its share of the world population is predicted to stay fairly stable from 1959 to 2050, at about 55 to 60 percent (UN 2007). The relative significance of Europe's population, on the other hand, has declined by almost half, from 22% in 1950 to 11% in 2005, and is predicted to decline even further to 7% in 2050 (UN 2007).

It is not the population itself that is important, but also the age composition of the population. As shown in Figure 1.1, the structure of the population in Germany has changed from the traditional pyramid shape in 1910 to an almost inverted pyramid shape predicted for 2050. The population of the 60+ age group will increase almost two fold in the next 25 years (WHO et al. 2002). However, the most dramatic changes will be seen in the 80+ age group. Europe is set to become the world's oldest region by 2025 (WHO et al. 2002). The reasons for this phenomenon of population ageing can be attributed to lower fertility rates and increased life expectancy (WHO et al. 2002, UN 2007). The ageing of the baby boomer generations and improvements in income and health also contribute to this trend (Pochet 2003).

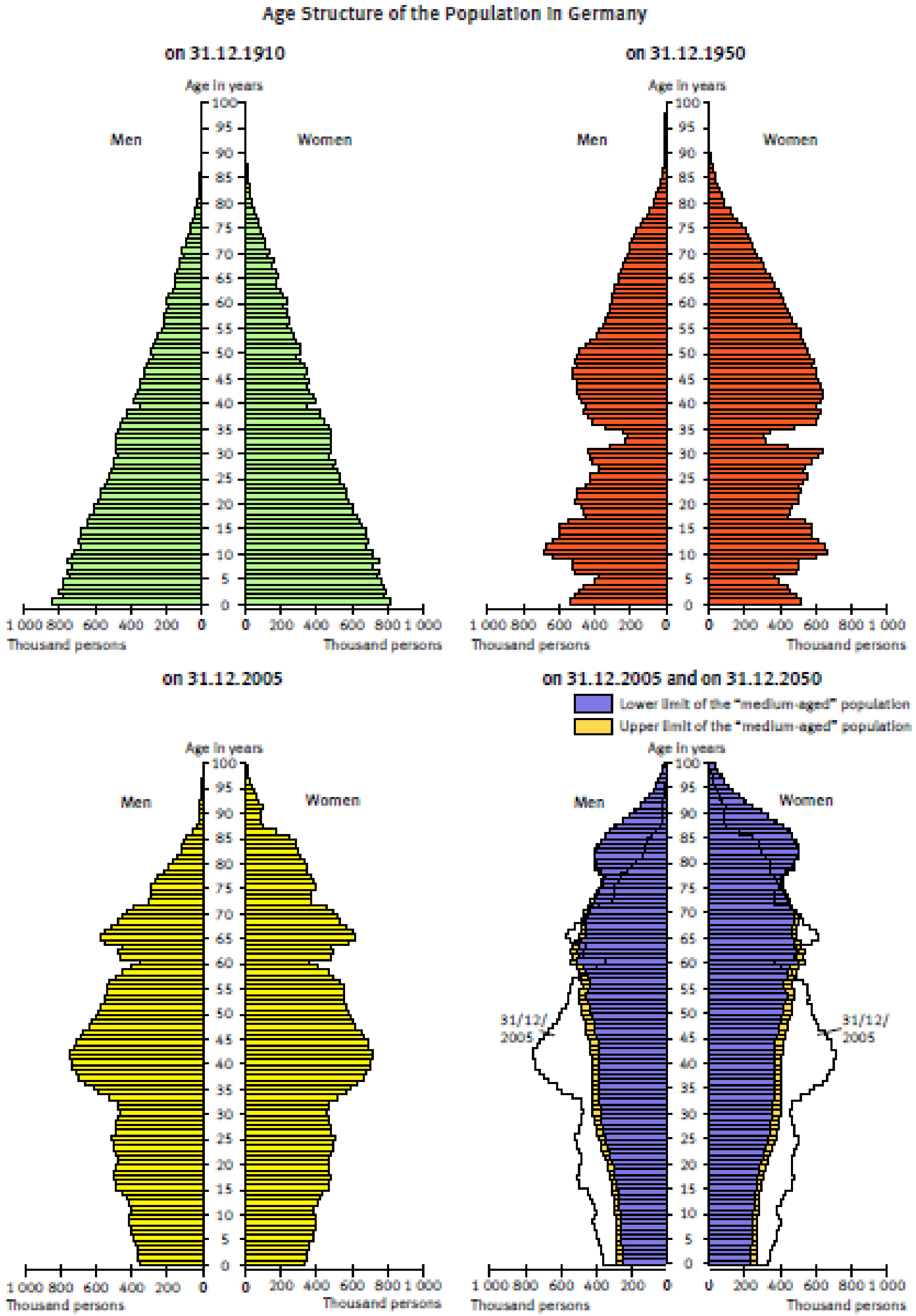


Figure 1.1: Demography of Germany in 1910 (top left), 1950 (top right), 2005 (bottom left) and the prediction for 2050 (bottom right). Adapted from the press copy of "Germany's Population by 2050 - Results of the 11th coordinated population projection", Statistisches Bundesamt, Federal Statistical Office, Wiesbaden

1.2 Physiological effects of aging

Aging is associated with a progressive decline of muscle mass, strength and quality, a condition described as sarcopenia (Thompson 2009) which derived from Greek literally means poverty of flesh. Aging affects the body from the bone to the tissue and skeletal muscle. Aging changes the physiological interplay of the immune, endocrine and nervous systems (Straub 2001). Height loss begins at around 30 years of age and accelerates with an increase in age (Sorkin et al. 1999). Body fat is redistributed with an increase in visceral fat combined with a decrease in subcutaneous fat on the limbs (Kuk et al. 2009). In addition, lipids are also deposited into the muscle (Haehling et al. 2010). Bones become weaker as a result of loss of bone tissue. The chondroid tissue, i.e. cartilage, menisci and invertebral discs, gradually lose their capacity to act as shock absorbers/spacers for joints while the ligaments lose their elasticity and thereby ability to absorb shock loading and return to anatomical shape (Freemont & Hoyland 2007). This is because with age, the structural proteins, collagen and elastin, undergo excessive cross-linking, leading to over-stiffening of the fibres (Bailey 2001).

The reduction in muscle mass is due to loss of muscle fibres and decrease in muscle fibre size, leading to strength reduction (Barrett & Lichtwark 2008) although the process is highly variable among muscle groups and individuals (Thompson 1994). Another reason for muscle loss is the loss of motor units due to denervation and a net conversion of fast type II muscle fibres into slow type I muscle fibres. There is also a loss in flexibility or range-of-motion of the various joints, the amount of decline differing between males and females, and on the type of joint (Chung & Wang 2009, Doriot & Wang 2006, Chateauroux & Wang 2008). In short, one can say that aging causes decline in strength and flexibility of the body.

To date, many investigations have been carried out on the different types of strength measurement in males and females, across various age groups, and within various ethnicities (Viitasalo et al. 1985, Cahalan et al. 1989, Lindle et al. 1997, Stoll et al. 2000, Voorbij & Steenbekkers 2001, Sunnerhagen et al. 2000, Xiao et al. 2005, Samuel & Rowe 2009, Kim et al. 2010). Skeletal muscle strength is the amount of force that a muscle or a group of muscles can produce in a single muscle contraction whereas torque refers to the amount of rotation in a limb as a result of application of such a force (Spirduso et al. 2005). Muscle strength is broadly classified into static or isometric strength and dynamic strength (Spirduso et al. 2005). Isometric strength refers to activation of a muscle without any change in its length. Dynamic strength involves a shortening (concentric strength) or lengthening (eccentric strength) of the muscles resulting in movement of a limb segment or the body.

Given the effects of aging and the dramatic demographic changes, it is becoming more and more important to provide support for the aging population in terms of evaluation and design of comfortable and safe environments at work and during activities of daily living. In today's state-of-the-art technology, digital human modeling is proving to be a useful and valuable simulation tool for ergonomics and digital human models are being incorporated into market-leading Product Lifecycle Management systems such as CATIA and UG. Digital human models help reducing development time and costs by allowing for in-silico tests of the interaction between products and humans before the products are materialized, as opposed to the costly and time-consuming experiments of traditional product development involving test subjects, focus groups and subjective evaluations (Porter et al. 1993, Chaffin 2001, Bowman 2001, Hanson et al. 2006).

1.3 Digital Human Modeling

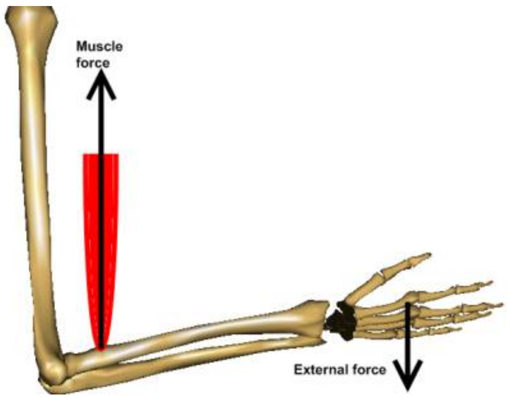
Digital human models or DHMs have been around for the past 50 years, having originated from the American air and space research field. The first DHM was developed by Ryan and Springer at Boeing Aircraft in the late 1960s to assess the reach of pilots of various anthropometries and predict an optimised posture. The model SAMMIE, based on 3D polygons, originates from the University of Nottingham, and used in the development of industrial work places, automobiles and utility vehicles. In the 1970s, the Chrysler Corporation developed a 3D wire model called CYBERMAN for the design of dashboards, seats and geometry of seat belts. The JACK human mannequin, consisting of 39 body elements, was developed by the University of Pennsylvania in the 1980s and 90s with a focus on vehicle design and architecture.

The computer man model SAFEWORK was developed at the Ecole Polytechnique in Montreal in the 1980s for safety and health evaluation. ERGOMAN was created in the mid 80s in France and is a 3D wire, plane and volume model. Under the supervision of Prof. Abdul-Malek at the University of Iowa in the late 1990s, the Virtual Soldier Research program was created and funded by the US military and corporate partners. This has led to the creation of the Santos™ biomechanical DHM in 2008 that provides posture prediction, strength, fatigue and physiology (SantosHuman™ Inc. 2012). In the late 1980s an extensive undertaking by the Technical University of Munich with support from Human Solutions and the German automotive industry resulted in the RAMSIS mannequin. This mannequin is used for posture prediction as well as comfort analysis. This paragraph of the history of digital human models has been adapted from Bubb & Fritzsche (2009).

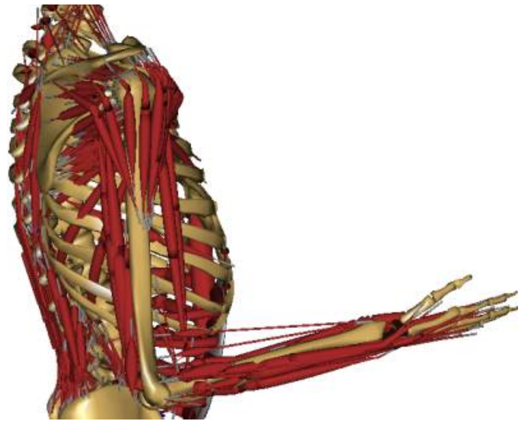
1.3.1 AnyBody Modeling System™

A relatively new DHM called the AnyBody Modeling System™ or AMS has been developed by an interdisciplinary group at Aalborg University in Denmark (Damsgaard et al. 2006). This system differs from most of its predecessors because it is a sophisticated musculoskeletal mannequin comprising several hundred muscles rather than an enveloped volume-based mannequin. The muscles or actuators are used to drive the individual limbs or rigid bodies. The environment is defined in terms of external forces and boundary conditions.

The software behind the system is not a black box but rather user programmable in an object oriented language similar to C++ called the AnyScript. A repository of body models and applications is made available to AnyBody users. However, users are also free to develop and use their own body and application models. This facilitates the development and exchange of information between users, thus allowing continuous improvement and validation by experts. An upgraded repository model is made available to all users on a regular basis. The user can impose any kind of posture or motion on the human body model from scratch or from a set of recorded motion data. AnyBody then runs a simulation and calculates the mechanical properties for the body-environment system. The results obtained include activation of individual muscle forces, joint forces and moments, metabolism, elastic energy in tendons and much more.



(a) The AnyBody general idea based on the principle of inverse dynamics



(b) The principle of inverse dynamics applied to a realistic human model

Figure 1.2: The principle of inverse dynamics applied to AMS

The AnyBody Modeling System^{TM} or AMS functions on the basic principle of inverse dynamics. As shown in Figure 1.2a, given the posture of the body and the external forces, by applying the laws of equilibrium the internal forces can be calculated. In theory the problem is a straightforward one, but as Figure 1.2b portrays, the reality is that there are infinite ways of muscle recruitment. Most joints have multiple degrees of freedom making analysis more complicated. There are also antagonistic muscles to be considered as well as the wrapping surfaces of muscles over bones. With all these factors in play, adding movement of the human body only enhances the complexity of the problem.

1.3.2 Strength scaling in AMS

In order that a model be useful in ergonomics, work place evaluation and product design in general, it is vital that it is scalable. Scaling alludes not only to anthropometry or percentile scaling of the human body, but also to age and gender. Besides being geometrically scalable, other physiological parameters like muscle insertion points, muscle parameters and wrapping surfaces also have to be considered. Although several scaling laws are available today, as briefly referred to earlier in this chapter, age and gender are important factors to achieve a more realistic strength scaled model. However there is a lack of consensus on the rate of strength decline over age for males and females. The fidelity of the DHMs depends intimately on valid estimation of strength. The development of age and gender-based strength-scaled equations for use in simulation models will therefore be of great value.

This work is based on an initial study to scale the AnyBody model at the University of Maastricht. Three different types of scaling laws were used to develop an elbow and knee model ranging from simple geometric scaling to a more complex law using age and gender as well (Annegarn et al. 2006). It was concluded that age and gender play important roles in strength scaling. Furthermore it was also stressed that the development of separate scaling laws for the knee and elbow were necessary. The participants in Annegarn's study ranged from the 20s to the 80s in age; however most of them were concentrated in the younger age groups (20-39 years).

1.4 General focus of the dissertation

Our study uses a similar test setup to Annegarn's work but focusses only on the older population of 50 to 79 years. Our purpose is to examine the effects of age, gender, body height, body mass, segment mass and segment length on maximal voluntary isometric contraction of knee extensors and elbow flexors. As compared to dynamic strength measurement, maximal voluntary isometric contraction is the simplest method to measure the strength of a particular muscle group because segment velocity and muscle length are maintained constant (Smidt & Rogers 1982). In addition to these parameters, overall pain and physical activity are obtained on a subjective basis using questionnaires in order to establish whether these parameters were correlated to strength. The variables are statistically analysed to determine which of them principally influence peak torque. To achieve this, two methods are used: multiple linear regression and cumulative approximation. Cumulative Approximation is a nonlinear programming technique developed by John Rasmussen (Rasmussen 1998). The results of both methods are statistically compared. The knee and elbow torque equations are then separately analyzed and validated both statistically as well as in AMS.

1.5 Outline of the dissertation

This chapter has given some preliminary background information leading to the focus of this project i.e. development of age and gender based strength scaling laws using the linear multiple regression and cumulative approximation methods. The next chapter is a literature review of studies measuring various types of strength across age and gender. This is followed by a detailed look into AMS and its scaling methods. Chapter 3 describes the methods of subject recruitment for the tests, and the experimental protocol. It also includes the post-processing and analysis of the data. Results of the study are presented in chapter 4. This is followed by the discussion in chapter 5 and the conclusion as well as future scope of the project in chapter 6.

2

Literature Review

The aim of this study is to develop strength scaled models of the older population aged 50 to 80 years based on age, gender and anthropometric parameters and then reduce the models to a sufficient and necessary set of dependent parameters by removing statistical redundancies.

In order to achieve this, a review of what is currently known about the influences of age, gender and various muscle groups on the different types of strength. Empirical studies over the past 10 to 20 years will be reviewed as well as key literature from earlier studies. Since the final goal is to introduce these scaling laws into the AMS, the various scaling methods in AMS will also be described in order to understand which parameters have already been implemented into the scaling laws and what kind of improvements need to be made. The models will be established using MLR and CA. Since MLR is a well-established method, no further details about its working will be mentioned. A brief explanation about the principle and working of CA will however also be included in this chapter.

2.1 Effects of age and gender on strength

As briefly explained in Section 1.2, aging is associated with a decline in strength in both males and females. The effect of age on strength however, depends on the type of strength measured (isometric VS concentric VS eccentric), the muscle group measured (upper body VS lower body), physical status of the individual and his or her disease status (Spirduso et al. 2005). It must also be noted that the speed of flexion or extension during dynamic strength measurement affects performance of that particular muscle group. As the speed of isokinetic testing increases, the torque decreases for concentric action and increases for eccentric action (Griffin 1987, Knapik et al. 1983, Danneskiold-Samsøe et al. 2009, Cahalan et al. 1989). This can be explained by the force-velocity relationship of Hill's muscle model as shown in Figure 2.1. The amount of strength produced by a certain muscle group also depends upon the joint angle of measurement (Knapik et al. 1983, Samuel & Rowe 2009) and on the posture of the individual during measurement (Bohannon et al. 1986).

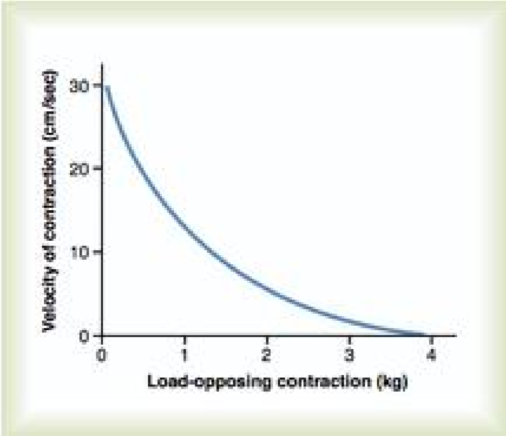


Figure 2.1: Force-velocity relationship of Hill's muscle model

Vidt et. al 2012 In 2012, Vidt et al. (Vidt et al. 2012) investigated upper limb muscle volume and isometric peak torque at the shoulder, elbow and wrist joints in 18 older adults above 65 years of age, and compared these data with previous reports of younger adults. Total muscle volume, functional muscle volume and isometric peak torque of older adults was lower than that of the younger adults with the most marked deficits shown in the shoulder. Older adults were not strongest in the shoulder like young adults. It must be noted that the sample size of this study was small due to which gender differences were not accounted for and the study could not be generalized to a population. Also, intramuscular fat was not measured due to time and participant constraints. This study was based on comparison with younger adult data from other studies which can introduce errors stemming from inter-rater reliability and use of different equipment.

Kim et al. 2010 Isokinetic and isometric strength of the knee and ankle joints of middle-age workers were compared with young workers and elderly adults (n=14 per group). It was found that the middle-age workers' leg strengths were significantly lower than that of the younger workers, but almost identical to that of the elderly adults. Knee flexors declined more in strength compared to the knee extensors in middle-age adults. Due to the small sample size, this study cannot statistically represent a population, and inferences between males and females cannot be drawn.

Demura et al. 2010 The hand grip power of elderly males and females (n=15 per group) in their 60s by assessing their maximum voluntary contraction and measurement of moving velocity of loads (30, 40 and 50% MVC). MVC of males was significantly greater than females whereas peak velocity and time to reach peak velocity at all loads was showed insignificant gender differences.

Yamauchi et al. 2010 The knee hip extension movements of 285 men (n=142) and women (n=143) aged 18 to 82 years under isotonic conditions was measured by Yamauchi et al (Yamauchi et al. 2009) in Tokyo, Japan. It was found that with an increase in age, the force generating capacity of the muscles decreased but no changes were found in the maximum shortening velocity of the muscles involved in the knee-hip extension movement.

Danneskiold-Samsoe et al. 2009 Danneskiold-Samsoe et al. measured the isokinetic and isometric muscle strength across the major joints in the body in a healthy population of 63 males and 126 females aged 20 to 80 years from Copenhagen, Denmark (Danneskiold-Samsøe et al. 2009). Subjects were grouped decade and gender wise, with the number of subjects ranging from 10 to 27 per group. Statistical models for the upper limbs, trunk and lower limbs were developed. As expected, females had lower strength than males in all age groups. Male strength decreased with age, whereas female strength was maintained until 41 years of age. The dependent parameters of the statistical models were height, weight, age and body mass index or BMI. Reduction of the models to age, height and weight for both genders was achieved. Male strength was mostly dependent on age, whereas female strength depended on weight and related to age only after 40 years of age. While this is quite a comprehensive study in terms of functional muscle groups measured, age range of the subjects, and development of statistical models, there is a dearth in the number of overall subjects. It must be noted that given time and resource constraints, there can be only so many hours that can be spent on good quality data collection. Hence, a tradeoff normally exists between sample size and number of muscle groups or types of strength measured.

Simoneau et al. 2007 In a study conducted by Simoneau et al. (Simoneau et al. 2007), the effects of joint angle and age on the MVC of the ankle dorsi- and plantar- flexors was examined in young (n=11) and old (n=18) men. The ratio of the dorsi- to plantar- flexor strength was measured and it was found that this value did vary with age and joint angle and was always higher with the older men because of the decline in plantar- flexor MVC torque with age.

Xiao et al. 2005 A sample size of 146 males and 47 females consisting of industrial workers, students and office workers were recruited in Ningbo, China. Their anthropometry and isometric MVC of grip strength, arm lift, shoulder lift and torso pull measured (Xiao et al. 2005). The isometric strengths of females were approximately 50% less than those of males. The authors compared their database with others and concluded that there were dissimilarities between American and Chinese datasets to the effect that applying a Chinese dataset to an American application would not be appropriate and vice versa.

Runnels et al. 2005 Runnels et al. investigated the influence of age on isometric, isotonic and isokinetic force in 75 males aged 20 to 83 years, distributed with approx 10 subjects per decade. The muscle groups investigated with the elbow flexors, elbow extensors, knee flexors and knee extensors. Lean body mass and bone-free lean body mass were determined from total body dual energy x-ray absorptiometry scans. Muscle performance declined more rapidly in the lower extremities than in the upper extremities, but only for isokinetic testing. The rate of decline of strength for all muscle groups and contraction type was most obvious at 60 years of age. Peak torque also decreased with increase in speed of contraction for all age groups and muscle groups. The time to reach PT increased with age, although this trend was significant only for the elbow flexors. It was found that lean body mass remained fairly constant with age even though muscle performance in general declined.

Ostchega et al. 2004 A big sample size of 1499 subjects (758 males and 741 females), approximately equally distributed in their 50s, 60s and 70s, were tested for maximal concentric PT of the right knee extensors. In addition, a timed-walk test over a 6 metre walkway. This population included different ethnicities (non-Hispanic whites, non-Hispanic blacks and Mexican Americans) and it was also investigated if there were racial differences in strength. Knee extensor strength decreased with age for both males and females (ca. 30% from 50 years to 70 years for both men and women). No significant racial or ethnic differences were found for either gender when mean PT was adjusted for height. However, the recruitment policy of this study did not include disability restrictions. Also, the effect of body composition was not taken into consideration. Hence caution must be used in applying the results of this study. The six-metre walk times increased significantly with each decade for males and females and there were significant overall differences as well between males and females. An increasing knee extensor strength was associated with significant increases in the speed of walking.

Akima et al. 2001 Testing of the PT during isometric and isokinetic knee extension and flexion was carried out on 164 volunteers (90 males and 79 females) aged 20 to 84 years in this study. Subjects were divided decade-wise from the 20s to the 80s. Using Magnetic Resonance Imaging, the cross-sectional area (CSA) of the quadriceps femoris at the mid-thigh was measured. Knee extension PT decreased with age at all angular velocities for both men and women. Isokinetic PT in both men and women was significantly higher in the 20s compared to the 40s to 70s. CSA of the quadriceps femoris was significantly correlated to the maximum knee extension torque in men and women. Peak isometric knee extension torque per unit of CSA decreased with an increase in age for men, but not in women.

Stoll et al. 2000 Stoll et al. tested the maximal isometric strength of 51 functional muscle groups (FMGs) in a sample of 543 volunteers (f=290, m=253) ranging from their 20s to 80s in age. The joints investigated were the shoulder, elbow, wrist, hip, knee, ankle and spine. Both right and left sides of the body were tested. Men were significantly stronger than women for all 51 FMGs. Change of strength with age differed significantly between gender in 15 of 26 of the upper FMGs and in 10 of 20 of the lower FMGs as well as in the cervical spine extensors and flexors. Greater strength differences between the upper FMGs were found than with the lower FMGs. Right side strengths were significantly higher than left side strengths although these differences were too small to be clinically relevant. A biphasic model with linear equations for strength medians was found to be applicable to all 51 FMGs for both males and females. The transition age for females was 55 years and for males was 49 years. During phase 1, the rate of strength decline for both males and females were not significant, and almost identical to each other. In contrast, the isometric PT decreased significantly during phase 2 with female strength decreasing at a steeper rate than males. Although this study is a comprehensive one in terms of age range and muscles groups investigated, the physical activity levels of the subjects were not recorded. Nor were any measurements of body composition made. Therefore the impact of the type of work or hobby of a person on strength was not included. The association between the muscle/fat proportion and muscle strength was also not investigated.

Sunnerhagen et al. 2000 144 persons (f=75, f=69) from the city of Gothemburg, Sweden were tested for isometric and isokinetic PT of the knee and ankle flexors and extensors. Hand grip strength, walking velocity and standing heel-rise test were also performed. Physical activity was subjectively recorded using a PASE (Physical Activity Scale for the Elderly) questionnaire. Biopsies of the vastus lateralis muscle of a subgroup were taken for histochemical and enzymatic analysis. Hand grip strength (peak and sustained over 10 seconds) was found to be significantly correlated to age for males and females for both right and left sides. Both hand grip strengths were also significantly correlated to the physical activity index for both genders and both hands. Women walked slower than men. Self-selected and maximal walking speeds reduced with age for both genders. Both speeds were significantly correlated to body height and step length. The highest number of heel-rises were performed by men in their 50s and women in their 40s.Isometric PT of the knee flexors and extensors was significantly higher for the right leg than the left for both genders. Isometric extension was highly correlated with age for the right leg but not for the left leg in both genders. In case in isometric flexion, males had significantly lower left leg strength than right leg strength. Isokinetic knee flexion and extension was significantly correlated with age for both legs in both genders. Left leg strength was significantly lower than for the right leg. Eccentric knee movement on the other hand was not statistically different between the two sides. Isometric endurance at

40% of isometric PT was measured in seconds and found to be highest for men in their 70s and women in their 40s. Interestingly, no relationship between physical activity index and endurance was found. In terms of ankle strength, a highly significant relation between age and dorsi flexion was found. The biopsy results showed no significant changes in fiber type distribution, fiber area and capillarization with age except for a few parameters. However, the authors conclude that the sample size maybe too small to show variations over age.

Lynch et al. 1999 The differences between arm and leg muscle quality (MQ) in men and women were assessed by measuring concentric and eccentric PT in 703 subjects (f=339, m=364) ranging from 19 to 93 years. In a subgroup of 502 subjects (f=278, m=224), body fat and fat free mass were measured using dual-energy X-ray absorptiometry. Muscle quality of a particular limb was calculated by dividing PT by muscle mass of that limb. Arm and leg MQ was found to be maintained until about 40 years of age after which the declines were quite large. Age associated decline of arm MQ was greater in males than in females although leg MQ declined at the same rate for both genders. For both genders, lower limb PT was significantly higher than upper limb PT and this difference decrease with age. In terms of MQ, the opposite was found to be true i.e. upper limb MQ was significantly higher than lower limb MQ. Males displayed a similar rate of decline of arm and leg MQ across age. However females showed higher decline in leg MQ than in arm MQ with age.

Rantanen et al. 1998 Due to time and financial constraints, not many longitudinal studies are carried out. An exceptional study in terms of sample size and time of follow-up was performed by Rantanen et al. where they measured the grip strength of Japanese men in Hawaii over a staggering follow-up period of ca. 27 years and studied the associations of rate of strength decline with weight change and chronic conditions. Over 8000 men aged 45 to 68 years were examined in the first session whereas ca. 3700 men were present at follow-up. Subjects who died before the follow-up study had significantly lower baseline strengths than survivors. The average decline in strength per year was 1%. A higher strength decline was associated with older baseline age, higher weight loss and chronic conditions such as stroke, diabetes. However, those subjects with a high baseline strength were more likely to have high strength at follow-up.

Lin et al. 1996 Lin et al. measured the isometric lifting strength of 350 Chinese adults (f=178, m=172) aged 20 to 81 years, living in Taiwan, in order to describe its effects from gender, age, body mass and height. Arm, back and leg lifting strengths were measured. For both genders, the order of strengths from strongest to weakest was leg, back and arm. Females on average had 57% the strength of males. Age was negatively correlated with age, while gender, body mass and body height were positively correlated with all types of strengths. A stepwise multiple linear regression model was developed to predict strength based on age, gender, body mass and body height. Gender was the most important predictor of strength. Body height was a predictor only for back strength. The amount of variance explained by this model between 63% and 72%. It is important to mention here that in this year of 1996, the authors end their note by stating that future research into the development of biomechanical simulation models is advisable for the prediction of isometric strengths based on anthropometric variables.

Bemben et al. 1991 The production of isometric muscle force as a function of age was investigated by Bemben et al. in 153 men with ages evenly distributed in 5 year intervals from 20 to 74 years. Muscle groups of interest were finger flexors, thumb abductors, forearm extensors, dorsiflexors and plantar flexors. Anthropometry and body composition were measured as well as the time to reach maximal force. Significant strength differences between age groups for all muscle groups were found. The greatest decline in PT was found in the forearm extensors and this decline began at 30 years of age. No significant differences between age groups for time to maximal force were found in any of the muscle groups. The maximal rate of force increase was also investigated and found to be significantly different between the younger group (20-59 years) and the older group (60-74 years). The effect of anthropometry and body composition on force-time curve variables were investigated but no effects were found.

Frontera et al. 1991 The effect of age, gender and body composition on the knee and elbow flexor and extensor strengths of 200 males and females age 45 to 78 years were investigated. Dynamic concentric strengths were bilaterally measured at slow and fast isokinetic speeds. For a subgroup, hydrostatic weighing was used to measure body density and thereby calculate fat free mass. Based on urinary creatinine, muscle mass was also calculated. No significant strength differences were seen between the dominant and non-dominant side. Strengths of the older group were significantly lower than those of the younger group. However, these differences were significantly reduced or almost completely eliminated when corrected of fat free mass and muscle mass was done. Women at all age groups and for all strengths had significantly lower strengths than the males. These differences were greater for the upper extremity than the lower.

Bohannon et al. 1986 Besides age, gender, body composition etc, another important parameter that affects strength is the posture of the body. This was proven by Bohannon et al. when they measured the isokinetic PT of the knee flexors and extensors in 14 females at low speed in the upright and semireclined sitting positions. Posture did not affect the knee extensor torque, but the upright position produced significantly higher flexor torque than the semireclined position.

Viitasalo et al. 1985 The muscular strength profiles and anthropometry of 250 males in age groups of 31-35, 51-55 and 71-75 years were investigated. Isometric PT of grip, elbow flexors and knee extensors was measured. Anthropometric measurements were used to calculate BMI, fat-free mass, percentage of body fat, fat mass and a weight factor. Body height, BMI and fat mass had the highest correlations with age. Age and strength were also found to be highly correlated. Of these strengths, grip strength was highest correlated with age and least affected by anthropometric parameters. BMI had the greatest controlling effect on the differences in isometric PT between age groups.

Pearson et al. 1985 An elderly group of 100 females and 84 males aged 65 to 90 years were tested for isometric PT of the plantar flexors and elbow flexors. Anthropometry was also measured. Strength declined significantly with age except in the female elbow flexors. Multiple linear regression analysis revealed that age, body mass and gender had independent effects on strength and explained 62% variance of plantar flexors and 84% of the elbow flexors. Strength of the calf muscle compared to body mass declined significantly with age for both males and females.

Young et al. 1985 and 1984 In two publications by Young and al. in 1985 and 1984, the size and isometric PT of the quadriceps muscles over age and gender were investigated. The females consisted of n=25 in their 70s and n=25 in their 20s. The older women were on average 35% weaker and their mean quadriceps CSA 33% smaller than that of the younger females. Both groups tested for a significant positive correlation between isometric PT and mid-thigh CSA. In case of the males, 12 males in their 70s and 12 in their 20s were put through the same test as their female counterparts. Older men were on average 30% weaker and their mean quadriceps CSA 25% smaller than the younger men. In terms of isometric PT and mid-thigh CSA, a strong positive correlation was found for the older men but not in the young group.

Table 2.1: Summary of literature review of strength studies. Included in the table are author, year, age groups, sample size, muscle groups investigated and brief summary of the results. Please note that columns 2 and 3 i.e. Age Range and Sample Size respectively are matched row-wise. However this is *not* true for the next three columns i.e. the information in these columns is stand-alone

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
Vidt et al. 2012	66–83	$f = 8$, $m = 10$	Isometric PT	shoulder ab/ad	PT of older group < PT of younger group
				elbow F/E	Shoulder strength highest in younger group
				wrist F/E	Wrist strength highest in older group
Samuel and Rowe 2011	60's, 70's, 80's	$f = 40$, $m = 42$	Isometric PT	knee F/E	80's strength < 60's strength by 14% for grip strength to 27% for hip abductors
				hip F/E, ab/ad	grip strength is not an indicator of lower limb strength
				grip strength	
Kim et al. 2010	18–34	$f = 7$, $m = 7$	Isokinetic PT	ankle df/pf	Middle aged workers sig. weaker than younger aged workers

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
	35–54	$f = 7$, $m = 7$		knee F/E	Older adults almost identical to middle aged workers
	> 65	$f = 7$, $m = 7$			Knee flexors declined more compared to knee extensors in middle aged adults
Demura et al. 2010	60–69	$f = 15$, $m = 15$	MVC	grip strength	MVC of males sig. stronger than females
			peak velocity		No sig. gender diff in peak velocity and time to reach peak velocity
Yamauchi et al. 2009	18–29	$f = 39$, $m = 55$	Isometric PT	leg press	Decrease in force generating capacity with age
	30–39	$f = 35$, $m = 35$			No differences in max. shortening velocity across all age groups
	40–49	$f = 12$, $m = 15$			
	50–59	$f = 17$, $m = 35$			

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
	60–	$f = 66$, $m = 27$			
Danneskiold-Samsoe et al. 2009	20–29	$f = 18$, $m = 10$	Isometric PT	All major joints	Male strength declines linearly from 25 years and more dependent on age parameter
	30–39	$f = 18$, $m = 10$	Isokinetic PT		Female strength depends on weight and declines with age from ca. 40 years
	40–49	$f = 23$, $m = 12$			Males are 1.5–2 times stronger than females in general
	50–59	$f = 18$, $m = 10$			Oldest males as strong as youngest females in general
	60–69	$f = 22$, $m = 10$			
	70–79	$f = 27$, $m = 11$			
Runnels et al. 2005	20–29	$m = 13$	Isometric PT	Knee F/E	Knee strength declines quicker than elbow strength but only for isokinetic testing

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
	30–39	$m = 14$	Isotonic PT	elbow F/E	From 60 years on strength decline is most obvious
	40–49	$m = 15$	Isokinetic PT		Lean body mass maintained ca. constant inspite of decline in strength
	50–59	$m = 10$			
	60–69	$m = 14$			
	70–	$m = 09$			
Ostchega et al. 2004	50–59	$f = 226, m = 207$	Isometric PT	Knee E	Knee extensor strength declines with age for both genders
	60–69	$f = 263, m = 278$	Timed-walk test		Walk times was sig. diff between gender and inc. sig. with age group
	70–	$f = 252, m = 273$			Knee extensor strength was associated with timed walk performance in males and females

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
Akima et al. 2001	20–39	$f = 5, m = 28$	Isometric PT	Knee F/E	Isokinetic extensor PT dec. with age for males and females
	40–49	$f = 5, m = 10$	Isokinetic PT 3		Isokinetic PT of youngest sig. higher than above 40s groups for both genders
	50–59	$f = 21, m = 9$	MRI of thigh		CSA of thigh sig. correlated to isokinetic extensor PT in men and women
	60–69	$f = 31, m = 26$			Isometric extensor PT per unit CSA dec. with inc. in age for men, but not for women
	70–84	$f = 16, m = 17$			
Stoll et al. 2000	20–82	$f = 290$	Isometric PT	51 FMGs	Female strength declines sig. from 55 years
	21-79	$m = 253$		right and left sides	Male strength declines sig. from 49 years
					Greater strength differences bet. upper FMGs than bet. lower FMGs

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
					Diff. between right and left side strengths although sig, too small to be clinically relevant
	40–49	$f = 19, m = 16$	Isometric PT	knee F/E	Grip strength sig. corr. to age and phy. activity index for both genders, and both hands
Sunnerhagen et al. 2000	50–59	$f = 15, m = 20$	Isokinetic PT	ankle df/pf	Highest no. of heel rises by men in 50s and women in 40s
	60–69	$f = 27, m = 18$	grip strength		Knee and ankle strength declines with age
	70–79	$f = 14, m = 15$	biopsies		Isometric endurance highest for men in 70s and women in 40s
			heel rises		No relationship between isometric endurance and phy. activity index found
			physical activity		Biopsy results not significantly different

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
Lynch et al. 1999	20–29	$f = 31, m = 23$	Concentric PT	knee F/E	Arm, leg MQ maintained until 40 years in m and f
	30–39	$f = 47, m = 36$	Eccentric PT 2	elbow F/E	Arm MQ decline greater in m than f with age
	40–49	$f = 105, m = 66$	body composition	muscle gp 3	Leg MQ decline at similar rate for m and f
	50–59	$f = 70, m = 65$			Lower limb PT sig. higher than upper limb PT for m and f
	60–69	$f = 44, m = 81$			Upper limb MQ sig. higher than lower limb MQ
	70–79	$f = 24, m = 58$			Decline of arm and leg MQ with age similar for males
	80–	$f = 18, m = 35$			Decline in leg MQ greater than arm MQ with age for females
Lin et al. 1996	20–29	$f = 30, m = 30$	isometric PT	arm liftin	For m and f, leg strength strongest and arm strength weakest
	30–39	$f = 32, m = 29$		leg lifting	Females have 57% of male strength

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
	40–49	$f = 28, m = 29$		back lifting	Stepwise MLR model to predict strength developed
	50–59	$f = 33, m = 26$			For above, gender is most important variable
	60–69	$f = 29, m = 29$			Body height important predictor of back strength
	70–	$f = 26, m = 29$			In addition, body mass and age are good predictors
	20–24	$m = 14$	isometric PT	finger flexors	PT sig. diff bet. age groups for all body parts measured
Bemben et al. 1991	25–29	$m = 15$		thumb abductors	Greatest decline in PT in forearm extensors
	30–34	$m = 16$		forearm extensors	Above decline begins at 30 years
	35–39	$m = 13$		dorsiflexors	No effect of anthropometry or body composition of force-time curve variables
	40–44	$m = 16$		plantarflexors	
	45–49	$m = 11$			

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
	50–54	$m = 16$			
	55–59	$m = 12$			
	60–64	$m = 17$			
	65–69	$m = 13$			
	70–74	$m = 10$			
Frontera et al. 1991	45–54	$f = 28, m = 24$	isokinetic PT	elbow F/E	No sig. bilateral strength differences found
	55–64	$f = 52, m = 28$		knee F/E	Older group sig. weaker than younger group
	65–78	$f = 34, m = 34$			When corrected for muscle mass or fat-free mass, significance almost disappears
					Diff. bet. female and male upper extremity strengths higher than lower extremity

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
Viitasalo et al. 1985	31–35	$m = 131$	isometric PT	grip strength	Body height, BMI and fat mass had highest corr. with age
	51–55	$m = 138$		elbow flexors	Age and strength were also highly correlated
	71–75	$m = 119$		knee extensors	Grip strength had highest correlation with age and least affected by anthropometry
Pearson et al. 1985	65–90	$f = 100, m = 84$	isometric PT	plantar flexors	Strength declined sig. with age except for female elbow flexors
				elbow flexors	MLR analysis showed age, body mass and gender to be important predictors of strength
Young et al. 1985, 1984	71–81	$f = 25$	isometric PT	quadriceps	Older women 30% weaker, mean thigh CSA 33% smaller than younger group

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Table 2.1 – continued from previous page

Study	Age Range	Sample Size	Strength	Muscle Groups(s)	Results
	20–29	$f = 25$			Isometric PT is sig. positively correlated to mid-thigh CSA
	70–79	$m = 12$			Older men 30% weaker, mean thigh CSA 25% smaller than younger group
	20–29	$m = 12$			PT and CSA have strong positive correlation for older men, but not for the younger men

2.2 Scaling digital human models in AMS

AMS is a simulation software of the mechanics of the human body in concert with the environment. The environment is defined in terms of external forces and boundary conditions. The user can impose any kind of posture or motion on the human body model from scratch or from a set of recorded motion data. AnyBody then runs a simulation and calculates the mechanical properties for the body-environment system. This includes more than 1000 muscle elements. The results obtained include activation of individual muscle forces, joint forces and moments, metabolism, elastic energy in tendons and much more. AnyBody can also scale the model anthropometrically to fit different individuals or populations.

In the work done by AnyBody Technology in collaboration with the Ford Research Centre in Aachen, Germany, a general scaling law has been developed and implemented in the public domain model repository. This law also allows the usage of user defined scaling laws.
The theory behind the scaling law involves two configurations; a reference configuration i.e. the existing AnyBody model based roughly on the 50^{th} percentile European male, for which all data is known, and a scaled configuration, for which only some data (mostly segment length and mass) is known and the remaining parameters have to be determined.

There are many ways of scaling, but AMS uses the simplest method i.e. linear scaling as shown in Equation 2.1, because of unavailability of data for other approaches.

$$s = Sp + t \tag{2.1}$$

where p is the original nodal position obtained from a cadaver study of MRI scan etc. S is a $3x3$ scaling matrix, t is the translation of the local coordinate system relative to the segment geometry and s is the resultant scaled nodal position on a bone. So we need to find the scaling matrix S and translation t in order to scale the particular nodal position. Different choices of S and t will lead to different scaling laws.

$$\begin{bmatrix} S_{11} & 0 & 0 \\ 0 & S_{22} & 0 \\ 0 & 0 & S_{33} \end{bmatrix}$$

2.3 Scaling laws in AnyBody

There are currently seven scaling laws available in AnyBody. The first four are joint-to-joint scaling methods while the remaining three are based on external body measurements. The scaling procedures are tested for geometrical and kinematical compatibility on the so called AnyFamily. This is a group of anthropometrically generated models created by Ramsis, based predominantly on segment lengths and masses.

2.3.1 Joint-to-joint scaling methods

Scaling Standard In this approach, there is no scaling done, so no member of the AnyFamily is used. This scaling law produces a default model in terms of mass and size, corresponding roughly to the 50^{th} percentile European male.

Scaling Uniform (Scaling Length) This law helps define tall or short people. The input is body mass which is distributed among segments by means of coefficients (Winter 1990) in the file $AnyMan$. This scaling file also specifies the bone length in terms of joint-to-joint distances which is then scaled uniformly by the model in all three directions. In this case, the scaling matrix S is given as follows with L_1 being the scaled length and L_0 the original length. S_{11}, S_{22} and S_{33} correspond to the x, y and z directions respectively.

$$S_{11} = S_{22} = S_{33} = k_L = \frac{L_1}{L_0} \tag{2.2}$$

The drawback of this approach is that it requires very good knowledge of anthropometry, and mistakes i.e. abnormally sized bones are possible. Therefore, it is also possible to input only body mass and height so that segment lengths are reasonably scaled. In this case the $AnyManUniform$ file is also used.

Scaling Length Mass Here, not only segment length, but also segment mass is scaled, so is it possible to define not only tall or short people but also thin or squat people. Input is still body mass and body height where the segments masses are distributed according to coefficients (Winter 1990). In the previous law, segment lengths are automatically scaled. But in this law, the segments lengths are multiplied by a factor depending on the height. The default model is based on a body height of $1.80m$. So we multiply the segment lengths by a factor of $1.98/1.80 = 1.1$. The bone segment is assumed to have a longitudinal structure and the local coordinate system follows the ISB conventions (Wu et al. 2002, 2005). The y-axis denotes the longitudinal direction, and the x and z the cross sectional directions. Hence y differs from x and z. y direction scaling is of the form:

$$S_{22} = k_L = \frac{L_1}{L_0} \tag{2.3}$$

where L_1 is the segment length of the scaled segment and L_0 is the segment length of the original segment. The mass ratio is obtained as:

$$k_m = \frac{m_1}{m_0} \tag{2.4}$$

where m_1 is the mass of the scaled segment, and m_0 is that of the original segment.

Hence we get scaling along the x and z directions as follows:

$$S_{11} = S_{33} = \sqrt{\frac{k_m}{k_l}} \tag{2.5}$$

Scaling Length Mass Fat This model works exactly like the LengthMass law except that the fat percentage is also taken into account. This is important to correctly estimate the strength of a person by distinguishing two persons of same mass but one having a higher fat percentage leading to lesser muscle and hence lower muscle strength.

Here the fat percentage R_{fat} is included in the estimation of scaled strength. If R_{muscle} is the percentage of muscle, and R_{other} includes the organs, blood, bone, cartilage etc, then we get Equation 2.6:

$$R_{muscle} = 1 - R_{fat} - R_{other} \tag{2.6}$$

The strength of the scaled model is subsequently given as:

$$F = F_0 \frac{k_m}{k_L} \frac{R_{muscle,1}}{R_{muscle,0}} = F_0 \frac{k_m}{k_L} \frac{1 - R_{other,1} - R_{fat,1}}{1 - R_{other,0} - R_{fat,0}} \tag{2.7}$$

where subscripts 1 and 0 represent the scaled parameter and the original parameter respectively. The fat percentage is calculated from BMI or Body Mass Index which in turn is calculated from body mass and body height (Frankenfield et al. 2001). It is also possible for a user to substitute this calculation of fat percentage with another approach or even with a fixed number if modeling an individual whose fat percentage is already known. R_{fat} for men is given as:

$$R_{fat} = -0.09 + 0.0149 * BMI - 0.00009 * BMI^2 \tag{2.8}$$

while R_{fat} for women is given as:

$$R_{fat} = -0.08 + 0.0203 * BMI - 0.000156 * BMI^2 \tag{2.9}$$

2.3.2 Scaling based on external body measurements

The previous four scaling laws are based on joint-to-join measurements. But some joint locations are located deep within the tissue and not easy to palpate and measure from the outside, eg. hip joint. In this case, another set of scaling methods are defined that are the same as the previous three, except that the segment lengths are external and AnyBody scales the bone lengths based on this information. The scaling file used in this case can be catered to a particular individual using the file $AnyManExternal$ or to an overall population percentile using the $AnyManExternalPercentile$ or $AnyWomanExternalPercentile$ files.

In the *AnyManExt* file, inputs are given as body mass and body height. As before, the masses of segments are calculated as coefficients of body mass (Winter 1990). The segment lengths differ in that they are constant values based on bony landmark distances measure by tape.

The anthropometric data of the population are presumed to follow a Gaussian distribution and with enough measured data it is possible to calculate the average or mean value, standard deviation and percentile values. The mean value also corresponds to the 50^{th} percentile, meaning that 50% of the population is larger and 50% is smaller than that exact value. Anthropometric data can be found in many sources, but the files used are based on The Handbook of Adult Anthropometric Measurements, Data for Design Safety, Department of Trade And Industry, United Kingdom. It is only required to change a single parameter i.e. the percentile value. The right regression function must also be selected so that the input percentile value falls within the right range.

The last law i.e. *LengthMassFat* scaling based on external body measurements is the latest law used in the AnyBody modeling system.

2.3.3 Scaling strength in human simulation models (Annegarn et al. 2006)

A study of considerable importance carried out at the University of Maastricht, Netherlands by Annagarn et al. (Annegarn et al. 2006), aimed at improving strength scaling in digital human models by including the influence of age and gender. In addition, strength scaling for different muscle groups (arm and leg) was investigated. This study was carried out in collaboration with the Research Department of Ford, Aachen, Germany.

The variables measured were masses and lengths of upper and lower segments, body height, body mass, age and gender. In addition the peak isometric torque at the right knee and elbow joints were also measured. The number of participants and their age characteristics are given in Table 2.2.

	Men		Women	
Age	Leg (n=34)	Arm (n=14)	Leg (n=29)	Arm (n=12)
Mean	45.0	30.3	37.0	25.8
SD	21.5	8.1	18.0	5.8
Min	19.0	24.0	20.0	21.0
Max	84.0	46.0	76.0	42.0

Table 2.2: Sample size and distribution of participants in strength scaling study by Annegarn et al. 2006

Three strength scaling methods of increasing complexity were validated with these measurements of global variables and measured strength. The strength predicted by each method was compared with the actual measured strength. The first two methods were validated using the AnyBody modeling system; scaling of mass only, and scaling of mass and fat in the second method. The third method was based all measured global variables, including age and gender, and used two approaches: Multiple Linear Regression (MLR) and Cumulative Approximation (CA). MLR is a well established model and will therefore not be explained in great detail in this dissertation. Although CA has been introduced for the first time in this section as part of the results of Annegarn et al. 2006, a detailed explanation is provided in Section 2.4.

The differences between predicted and measured strengths for each method were statistically analysed in SPSS, for the leg model and the arm model separately. The mean difference between the measured and predicted strengths (as a scaling factor), correlation (r) and variance (R^2) for each method are presented in Table 2.3.

	Leg model			Arm model		
	Mean difference	r	R^2	Mean difference	r	R^2
Mass	2 %	0.39	0.15	37 %*	0.64	0.41
Mass-Fat	7 %*	0.60	0.36	36 %*	0.89	0.80
MLR	0 %	0.68	0.46	2 %	0.92	0.85
CA	1 %	0.88	0.78	0 %	0.99	0.99

Table 2.3: Strength scaled models by Annegarn et al. 2006 for the mass, mass-fat, MLR and CA methods for leg and arm. Mean difference between the predicted and measured strengths, correlation (r) and explained variance (R^2) for each method are shown. * implies a significant mean difference (p value unkown).

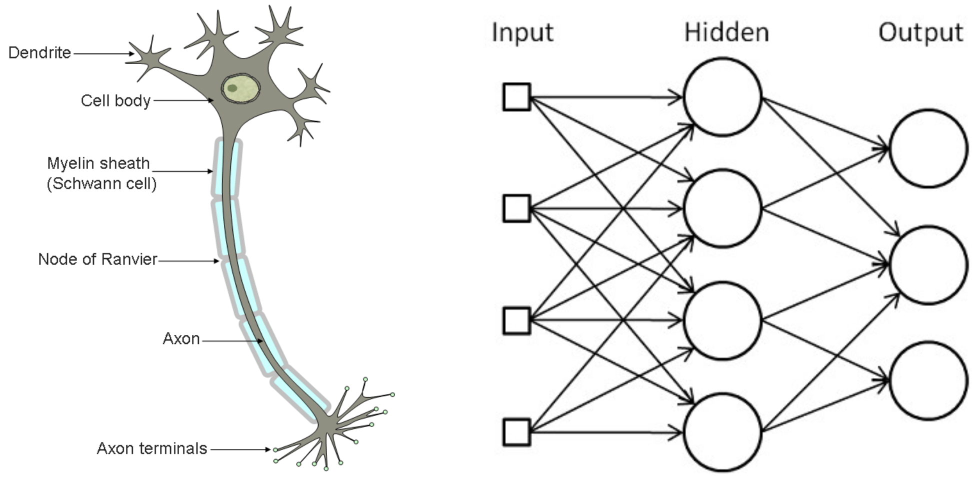
The CA and MLR approaches have the lowest mean difference. CA has the highest correlation and variance for both arm and leg models. The mean difference for the $Mass$ and $(Mass - Fat)$ methods of the leg model are much lower than those of the arm model, but they also have much lower correlations and variances. It was found that for CA, the influence of age, gender and mass of the upper segment had the strongest influence for both the arm and leg models. In the case of MLR, body weight was a strong influence for the leg model, as well as body height for the arm model.

From these results, it can be concluded that age and gender did indeed improve the accurate prediction of strength. Of all the models used, CA was found to be the most accurate predictor of strength. In addition, the need for different scaling equations for different muscle groups was also observed.

2.4 Cumulative Approximation

Evolution of the human brain has resulted in many desirable traits such as high parallelism, non-linearity, adaptability, generalization ability, fault and noise tolerance, low energy consumption. Inspired by biological neural networks, researchers across a range of scientific disciplines have attempted to design artificial neural networks to solve a host of problems from pattern recognition, prediction, optimization, associative memory, control etc (Jain & Mao 1996).

A brief look into the operation of the biological neuron can provide a better understanding of the artificial neuron. Referring to Figure 2.2a, signals or impulses are received by a neuron via the dendrites. These signals are transmitted along the axon, to the terminal buttons and to other neurons by jumping the synaptic gap between neurons.



(a) The biological neuron sourced from http://medicalpicturesinfo.com/neuron/

(b) The artificial neuron

Figure 2.2: The biological and artificial neuron

An artificial neuron, receives inputs as stimuli, combines them in a special way to form a net input, passes them over a linear threshold gate, and transmits the output to another neuron (Basheer & Hajmeer 2000). Artificial Neural Networks (ANNs) are classified into feedforward and feedback networks. Feedforward ANNs are more straight forward where signals travel in one direction only, from input to output i.e. there are no feedback loops. These ANNs are extensively used in pattern recognition. Feedback networks can have signals moving in both directions via feedback loops introduced in the ANN. They are very powerful, highly dynamic until they reach a point of equilibrium, and extremely complicated.

The most basic ANN consists of three layers; the input layer, the layer of hidden units, and the output layer as depicted in Figure 2.2b. The input units represent the data that is fed into the ANN. The hidden units perform based on the activity of the input units, and the weights on the connections between the input and the hidden units. The output units depend upon the activity of the hidden units and the weights between the hidden and output units. An ANN without any hidden units is called a perceptron and can only solve linear functions so is not very powerful. Multilayer feedforward ANNs on the other hand are more useful because they can solve nonlinear functions.

The Radial Basis Function or Cumulative Approximation (CA) network is a type which has two layers and is a special class of multilayer feedforward network. The advantage of CA is that there is no presumption of a functional relation between the inputs and outputs and data is fitted regardless of the internal dependencies. This is a huge advantage in studies such as ours where the exact relationship is not known. The disadvantage however is that unlike MLR, this method cannot extrapolate data.

CA makes use of a parameter called the blending factor. This factor has a normal distribution and its value can affect the outcome of an analysis. The smaller the blending factor, the narrower the distribution and the lesser the influence of the other data points of the dataset. The danger of a very small blending factor is that although the approximated curve will follow the datapoints very well, the result will look rather noisy. The higher the blending factor, the larger the influence of other data points and the smoother is the approximated curve.

CA method utilises the leave-one-out method of cross validation. In this method, one participant's data is removed from the original set of n samples. The model is built with the remaining $n-1$ samples, and the model is applied to the left-out subject. This process is repeated for each subject iteratively. From a computational point of view, this method can be quite intensive since it builds and tests the model n times.

Ideally the predicted strength should be equal to the true strength i.e. if a linear regression of the true and estimated strengths is calculated, the slope of the line should be ideally one, and R^2 ideally 100%.

The convex hull is the smallest convex set containing all the data points. Thus, in multiple dimensions, the boundary of the convex hull constitutes the border between interpolation and extrapolation. In our analysis, in every iteration of the leave-one-out, a check is made if the left-out subject falls within the convex hull of the remaining subjects. For more information on CA, please refer to Rasmussen (1998).

2.5 Summary of literature review

It can thus be seen that on the one hand numerous studies over the past decades have been undertaken to measure and understand which parameters affect the different types of strengths and to what degree. The list is comprehensive, and there is a general consensus that strength does decline with age. However, the differences between males and females, muscle groups, static or dynamic, speed of measurement tends to vary between studies.

Isometric torque of the hip joint was found to be higher than isokinetic torque for all degrees of freedom (Cahalan et al. 1989). This was also found true for the knee and elbow flexors and extensors (Griffin et al. 1993). It has been reported that eccentric action produces greater torque than concentric action (Danneskiold-Samsøe et al. 2009, Griffin 1987, Lynch et al. 1999). Strength measured by concentric action decreases in a manner similar to isometric strength. Eccentric strength on the other hand seems to be better preserved with age (Pousson et al. 2001). Muscle performance decreases significantly with age at all, i.e. slow, medium and fast speeds, of isokinetic testing (Jubrias et al. 1997).

It has been reported that the muscular strength of the lower body is higher than that of the upper body (Lynch et al. 1999). Studies have found that lower body muscle strength declines more rapidly with age than that of the upper body (Runnels et al. 2005*a*, McDonagh et al. 1984). Comparison of the arm, leg and back lifting strength over age has revealed that the decline in leg lifting strength was the most prominent (Lin et al. 1996). Concentric and eccentric peak torque of the leg is higher than that of the arm, but the difference narrows down with age in both men and women (Lynch et al. 1999).

That males on average have a higher strength than females across all ages, muscle action and speeds of testing is well established(Lindle et al. 1997, Lynch et al. 1999, Stoll et al. 2000, Pearson et al. 1985). With age, strength of both men and women decreases (Lindle et al. 1997, Yamauchi et al. 2009, Voorbij & Steenbekkers 2001). Different rates of age-associated changes have been observed for men and women in terms of concentric and eccentric peak torque of the arm and leg (Lynch et al. 1999). Stoll et al compared the strength of men and women in over 51 functional muscle groups, and found that the strength of women changing with age was significantly different to men in the majority of the muscle groups tested (Stoll et al. 2000). However, age accounts for lesser variance in eccentric peak torque for women than men (Lindle et al. 1997). Xiao et al (Xiao et al. 2005) found that the isometric strength of women was on average half that of men for various movements including grip strength, arm lift, shoulder lift and torso pull.

It has been reported that male industrial workers have higher isometric strength than students or males with desk jobs (Xiao et al. 2005). In a 5-year longitudinal study conducted in Finland, the authors found that individuals who maintained their activity preserved their strength at a higher level than their sedentary counterparts (Rantanen et al. 1997).

In addition, overall pain and physical activity will be recorded on a subject basis in order to establish the correlations of these parameters to strength. Multiple linear regression and cumulative approximation will be used to develop scaling equations and minimize them to a sufficient and necessary set of dependent variables based on statistical redundancies. The models will be compared with each other as well as validated both statistically as well as in AMS.

2.6 Aims, limitations and hypotheses

The scaling algorithms in the AMS lack the input of age and gender as well as the option to scale different functional muscle groups differently. As proven in the research, these factors are essential toward a robust strength scaling law. This project therefore aims at the development of an age and gender based scaling of strength.

Since this investigation is sponsored and run for Daimler AG, the test design will be based upon the relevance of the AMS software to the customer base of this particular automotive company. The average clientele buying a Mercedes-Benz belongs to the older age group of about 60 years. Keeping this in mind, we will focus on the older population of males and females ranging from 50 to 79 years. The subjects will be grouped decade-wise i.e. 50-59 years, 60-69 years and 70-79 years with the aim of having 50 males and 50 females in each group. One should bear in mind that the sample of subjects used in this study are based on their readiness to participate and not on factors such as physical activity, mental health, nutritional status etc. Also, this study is a not a longitudinal one, nor is repeated testing done over a period of time except for a small percent of participants to assess the reliability of the data acquired. These are the limitations of the database.

This study is part of a collaborative venture (AnyBody Cooperation Project) between Daimler AG, Ford-Werke GmbH and BMW AG in order to develop AMS for use in the automotive industry. The pilot study of strength scaling was run by Ford and the University of Maastricht. Certain aspects of our test design will therefore be based on the pilot study.

As compared to dynamic strength measurement, maximal voluntary isometric contraction is the simplest method to measure the strength of a particular muscle group because segment velocity and muscle length are maintained constant (Smidt & Rogers 1982). The aim is to focus on one upper body and one lower body joint and compare them. The knee and elbow are selected because they are involved in many activities of daily living and are relatively uncomplicated in terms of number of degrees of freedom. We will examine the effects of age, gender, body height, body mass, segment mass and segment length on maximal voluntary isometric contraction of the knee extensors and elbow flexors. Although peak isometric torque is the simplest of its kind, in reality, day to day living includes mostly dynamic movement. Keeping this in mind, maximal voluntary isokinetic concentric flexion and extension of the knee and elbow joints will also be measured and the data analysed in a separate project.

A full body scan using laser technology will be performed in order to obtain anthropometric data. Segment masses will be estimated from segment circumferences without taking into account the proportion and densities of underlying fat, muscle and bone. This is a limitation of the test design. Information about pain and level of physical activity of the participants will be gained from questionnaires. The knowledge of subjective pain will only be used as a control check in case of outliers in the data. Although it is well known that physical fitness and strength are significantly correlated, doing a fitness check and obtaining an objective result is out of the scope of this project. This is another limitation that has been considered before-hand.

After investigating the distribution and characteristics of the data acquired, the elbow and knee models will be established and condensed to a set of sufficient and necessary predictors using MLR. The models will then be validated using the 2-fold and leave-one-out methods of cross-validation. An elbow and knee model based on the CA method will also be established. The new scaling laws will then be applied in AMS and their performance compared with the existing Anybody scaling law i.e. length-mass-fat. The hypotheses of this study are: the models should show that age and gender are important and necessary predictors of strength. The cumulative approximation models should be more accurate than the regression models. The strength predicted form the new equations should be closer to the true strength than that predicted by the current AMS scaling laws.

If and when the above statements proved to be true then the next set of questions to be answered are: For what percentage of our population do the new scaling laws hold true? Are there trends in those participants in which the laws fail to apply? What are the improvements of one scaling law over the other?

3

Methods and Materials

The goal of the project is to develop a law that scales the strength of a person dependent on the following variables: body part, age, gender, height, body mass, segment length, segment mass.

In order to decide on which body part or joint to measure, a combination of natural exclusion and necessity was used. The neck joint, and the spine in general are very complicated to measure and scale. The shoulder and hip joints are both ball and socket joints with multiple degrees of freedom. Although the wrist and ankle joints are available in AMS, the hand and foot segments are not fully modeled yet. In comparison with all these joints, the knee and elbow are relatively simple with only one degree of freedom. Moreover, most movements of daily living include the motion of the knee and elbow. It was also important to test the entire methodology of the project with relatively simpler joints and later based on experience and success, move on to more complicated issues. Keeping these factors in mind, the elbow and knee joints are selected for strength measurement.

3.1 Subject recruitment

The focus of our study was on the older population of males and females aged 50 to 79 years. The inclusion criteria for the study were independent living and no debilitating conditions such that their doctor or physician would advise against participation. Participants were recruited from the Munich area of Germany. The age groups were divided decade-wise i.e. 50-59, 60-69 and 70-79 years with approximately 50 males and 50 females per group.

With the help of students from the university, subjects were externally and internally recruited from all walks of life. Different strategies for recruiting subjects were employed including street marketing, hanging flyers in public places, telemarketing and email newsletters. The resultant subject population were from the university, various sport and fitness institutions, senior study groups, shoppers at super markets, passer-bys and friends and family of already acquired subjects. The word of mouth propaganda seemed to have the highest effect. As a compensation for their time and effort, each subject was offered €20 plus a personalised anthropometric chart with body-mass index and hip-waist ratio.

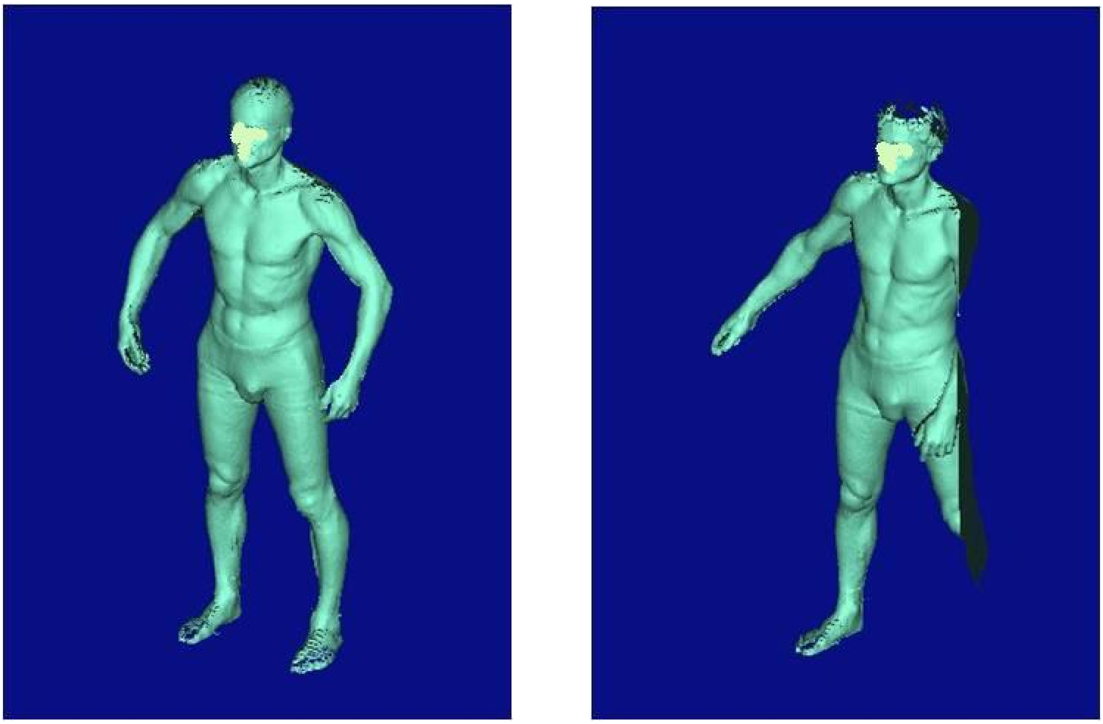
3.2 Questionnaires

At the start of the experiment, each subject was explained the goals and procedure of the study and required to give his/her written informed consent. All subjects were asked to fill out a pain questionnaire marking on a chart where they were currently experiencing pain and rating overall pain from 0 to 10. Please refer to A.2 for the pain questionnaire.

Subjects were also questioned about their physical activities over the past seven days in various domains (work, home, recreation, sport, travel) according to the International Physical Activity Questionnaire (Hagströmer et al. 2007). The amounts of time spent during different activities were transformed into a score and these scores were categorized into low, moderate or high physical activity. This was done using the guidelines for data processing and analysis of IPAQ (The IPAQ Group 2011).

3.3 Anthropometric measurement

A 3-D total body scan was performed using optical triangulation or laser technology (Model Vitus SMART, Human Solutions GmbH, Kaiserslautern, Germany) to determine the anthropometric measurements in accordance with the ISO 20685 standard. The posture adopted was a standardised one as prescribed by this company, see Figure 3.1a. However, this posture was not adequate in terms of obtaining specific information about the arm and leg segments in order to calculate segment volumes and then estimate segment masses. The reason for this is that the drawback of this type of scanner is the inability to scan relatively flat surfaces such as the top of the head, shoulders and feet. Other areas difficult to scan are the arm pits and the inner thighs. These latter issues are compounded with overweight or obese subjects. To attain better arm and leg scans, another posture, as shown in Figure 3.1b was used where the right arm and right leg were stretched out. A customized program was written to select the upperarm, forearm, thigh and shank segments and divide each segment into 19 equally spaced parts. The scans were created and analyzed in the Anthroscan V2.9.9 software.



(a) 3 dimensional scan in the standard posture

(b) 3 dimensional scan in the customised posture

Figure 3.1: Standard and customised postures adopted to obtain basic anthropometric information and calculate upper limb and lower limb volumes respectively

3.4 Muscle strength measurement

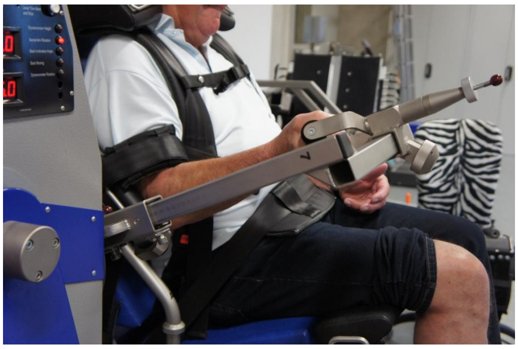
Peak torque was measured during a maximal voluntary isometric contraction of the right knee extensors and right elbow flexors using the IsoMed 2000 dynamometer (D&R Ferstl GmbH, Germany). All subjects first performed a 10 minute warm-up on an ergo meter starting at 2W and ending at 100W, speed between 60 and 90 rpm.

Knee torque measurement

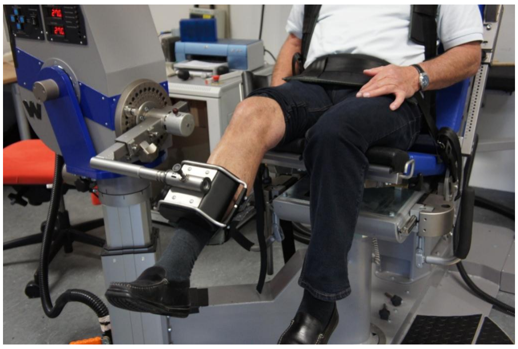
For knee torque measurement, the seat pan was inclined at 20 ° to the horizonal and the backrest tilted 110 ° backward with respect to the seat pan. The subject was then instructed to sit upright in the IsoMed seat and the backrest adjusted such that there was approximately 2-3 fingers spacing between the seat and the inside of the subject's knee.

The rotational axis of the dynamometer was aligned with the lateral femoral epicondyle, and the resistance pad fitted such that it lay approximately over the mid-tibia. A goniometer was used to measure the anatomic joint angles of 80 ° and 90 ° and the IsoMed was calibrated to these angles. Joint angles of 80 ° and 90 ° were selected based on the experimental protocol from University of Maastricht (Verdijk et al. 2009). Shoulder, chest and pelvic restraints were used to ensure minimal movement during measurement. The right thigh was also strapped to the seat as shown in Figure 3.2b. In addition to the physical limitations of movement, the subject was instructed to place his hands on his lap during measurement and try to use only the lower limb muscles for contraction. The subject then carried out approximately 12-15 knee flexion-extensions at a moderate speed, in the range 30° to 100° to ensure the specific lower limb muscles were sufficiently warmed. Maximum voluntary knee extension torque was measured at 80° and 90°.

In addition to isometric peak torque, it was decided to also measure the peak concentric torques during knee flexion/extension between 30° and 100° at a speed of 60°/*sec*. The isokinetic torque has been acquired even though it will not be used in this study in order to provide the basis for further data analysis to be carried out.



(a) Isomed setup for measurement of peak isometric elbow torque flexion



(b) Isomed setup for measurement of peak isometric knee torque extension

Figure 3.2: Setup on the IsoMed 2000 dynamometer for peak torque measurement of the elbow and knee

Elbow torque measurement

For elbow torque measurement, the seat pan was in the horizontal position and the backrest at 90° with respect to the seat pan. Once the subject was comfortable and seated upright, the upperarm was supported circa midway between the shoulder and elbow by a pad as shown in Figure 3.2a. The position of the handgrip was adjusted so that the shoulder was slightly abducted and the subject had a good grip on the handle. The rotational axis of the dynamometer was aligned with the lateral humeral epicondyle and the lever arm was approximately parallel to the forearm. A goniometer was used to measure anatomic elbow angles of 70°, 80° and 90° and the IsoMed was calibrated to these angles. These joint angles were also selected based on the experimental protocol from University of Maastricht. Similar to the knee, the subject's movements were restricted with shoulder pads, a chest strap and a pelvic strap. The upper arm was also strapped to the Isomed. The subject was instructed to place his left hand on his lap at all times, and encouraged to focus on contraction only with his right limb muscles without bending the wrist. The subject first performed 12-15 training repetitions between 40° and 140° at a moderate speed. Maximum voluntary elbow flexion torque was then measured at 70°, 80° and 90°.

The constraints were required to be as tight as possible, but the subject was asked to give feedback if they were too tight so as to be uncomfortable or cause pain. For both types of measurement, two trials per angle were measured with each trial lasting 4-5 seconds. There was a 2 minute interval between trials. All trials within each muscle group were randomized. The peak torque after each trial were noted, and if its value exceeded the ±10% range of the previous trials for that subject, then additional trials were performed until the maximal torque stabilized within the ± 10% range. The same verbal encouragement was given during each trial.

In addition to isometric peak torque, it was decided to also measure the peak concentric torques during elbow flexion/extension between 40 ° and 140 ° at a speed of 60 °/*sec*. As with the knee measurements, isokinetic torque has been acquired even though it will not be used in this study in order to provide the basis for further data analysis to be carried out. A test-retest study was performed to determine the reliability of our apparatus and experiment protocol. Eight subjects were tested twice with a one week interval. The entire study was performed by the same investigator and in accordance with the Declaration of Helsinki.

3.5 Segment mass calculation

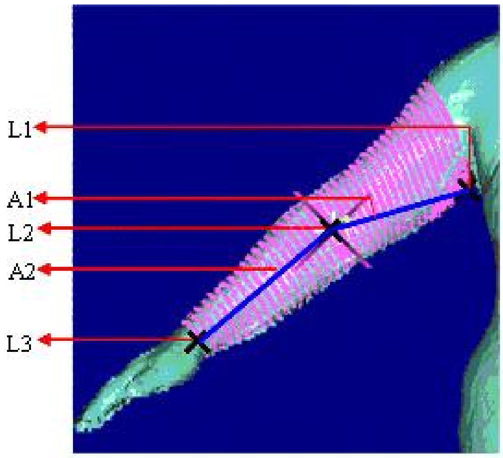
The customised bodyscan was used to calculate the segment masses. The upperarm and forearm were defined by manually selecting landmarks in the armpit, mid-point of the elbow and styloid process of the ulna in the frontal plane as shown in Figure 3.3a. The thigh and shank were defined by manual selection of the following landmarks in the sagittal plane: beneath the buttock line, midpoint of the femur-tibial knee joint and above the lateral malleolus. Refer to Figure 3.3b. Each segment was further subdivided into 19 equally spaced parts, and the girths and height were calculated. Each part was simplified as a truncated cone and its volume calculated as shown in Equation 3.1 where h is the height of the cone and R_1 and R_2 are its radii .

$$V = \frac{\pi * h}{3}(R_1^2 + R_2^2 + R_1 * R_2) \tag{3.1}$$

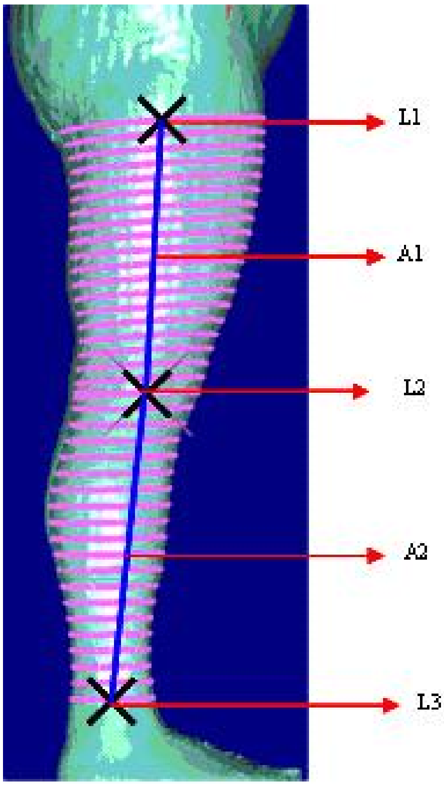
Summation of all cone volumes resulted in total segment volume. Estimating density of the human body to be 1.06 gm/cc (Annegarn et al. 2006), segment mass was calculated by multiplying volume by density.

3.6 Joint torque calculation

A sample plot of the elbow and knee torque are shown in Figure 3.4. The elbow and knee torque data were filtered at 10 Hz with a fourth order Butterworth low pass filter. The absolute maxima of each trial were found and its average over a 20 msec bin calculated to give the peak torque value for that trial. The peak elbow or knee joint torque of each subject was the highest peak torque within all trials. All data analysis was done in



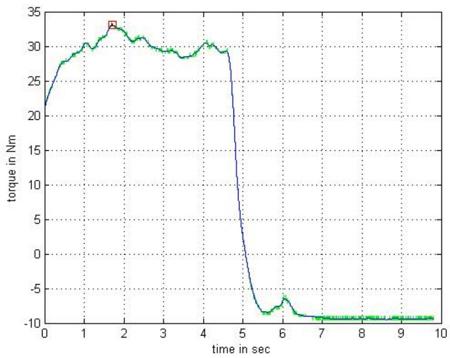
(a) Body scan of upper limb. L1, L2 and L3 are the upperarm, elbow and wrist landmarks respectively. A1 and A2 are the upperarm and forearm lengths respectively



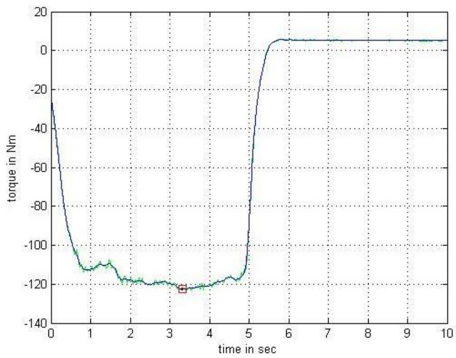
(b) Body scan of lower limb. L1, L2 and L3 are the thigh, knee and ankle landmarks respectively. A1 and A2 are the thigh and shank lengths respectively.

Figure 3.3: Calculation of segment volumes from body scans

Windows using the computing software Matlab (V R2007b).



(a) Sample peak isometric elbow torque



(b) Sample peak isometric knee torque

Figure 3.4: Sample peak isometric torque: raw data in green, 10 Hz second-order lowpass forward and backward Butterworth filter in blue, the red box indicates the maximum torque over a 20 msec moving average bin

3.7 Statistical analysis

Subjects were divided into three age groups as shown in Table 3.1. Exploratory data analysis was carried out to examine each of the six groups for normality. This was done by visual observation of the histograms and Q-Q plots. The numerical values of skewness and kurtosis were checked if they fell within the ±2 range. The results of the Shapiro-Wilcox test were also checked (this test was selected because it can handle small populations of < 50. Analysis of variance was used to compare the age group and gender differences in height, body mass, segment lengths and segment masses. When a significant difference was found, Tukey's HSD post-hoc test was performed to determine which comparisons were significant. Factor analysis was used as a method of data reduction by seeking out underlying relationships between the variables. The principle component analysis method of extraction based on eigenvalues greater than one was adopted along with the varimax rotation method. This statistical analysis was performed using SPSS statistical package (V 18.0.1) in Windows.

	50–59 yr (50s)	60–69 yr (60s)	70–79 yr (70s)
Male	$n = 40$	$n = 50$	$n = 49$
Age, yr	55.2 ± 3.1	65.5 ± 2.9	73.7 ± 2.9
Height, cm	174.6 ± 6.1	174.2 ± 5.7	171.3 ± 7.4*
Body mass, kg	78.3 ± 11.4	78.9 ± 10.5	78.4 ± 12.5
Female	$n = 42$	$n = 52$	$n = 50$
Age, yr	54.7 ± 2.9	65.4 ± 2.9	73.7 ± 2.4
Height, cm	162.9 ± 6.9	163.2 ± 6.2	160.8 ± 5.7*
Body mass, kg	66.8 ± 11.7	67.9 ± 10.0	64.7 ± 10.9

Table 3.1: Subject characteristics: Values are Mean ± SD; n=number of subjects; Males are significantly taller ($P < 0.05$) and heavier ($P < 0.05$) than women in all age groups. *Significantly different from all other groups ($P < 0.05$).

MLR analysis was performed to establish separate strength scaling equations for the elbow and knee. Statistical redundancies were removed in order to attempt to create a simplified equation of necessary and sufficient dependencies. The criteria for removal of independent parameters were the following; the Durban-Watson statistic should be 2.0 so that assumption of independence of errors is met, the average variance inflation factor (VIF) should be 1.0 so that multicollinearity does not bias the model, condition indices should not be greater than 25 and the explained variance (R^2) should not reduce greatly (Field 2009). MLR analysis was also performed using SPSS statistical package (V 18.0.1) in Windows.

Cumulative Approximation technique was also used to investigate strength scaling equations. In this method, the independent parameters are arranged into a matrix where the rows are the individual tests for each subject and the columns contain the measured properties of the given subject. One subject's data is removed from the column and CA is carried out to predict that subject's strength. This process is repeated iteratively for n subjects. In an ideal situation, the predicted strength will be identical to the actual strength, in which case plotting both strengths will result in a regression line with a slope of 1. In reality, this slope will differ from 1. The blending factor is varied from 0.0 to 1.0 in steps of 0.1 in order to ascertain which value results in a regression slope closest to 1.0. The algorithm for CA was obtained from the author John Rasmussen and implemented in Matlab (V R2007b).

3.8 Statistical validation

In order to assess the knee and elbow models, two forms of cross-validation were employed. The simplest form was 2-fold cross-validation where the dataset was split randomly into two subsets, each approximately 50% in size. MLR was carried out on each subset and the results compared with the other subset and the actual model. This procedure was implemented for both knee torque and elbow torque data using SPSS statistical package (V 18.0.1) in Windows.

The second form of cross-validation employed was the leave-one-out method where a subject's data was excluded from the database to form the validation data, and the remaining $n-1$ subjects formed the training set. MLR was applied to the remaining $n-1$ samples. The left-out subject's torque was then predicted and plotted against his actual measured torque. This procedure was iteratively repeated n times such that every subject was once and only once removed from the original sample set. To quantitatively assess how good the model is, the measured strength is plotted against the predicted strength and a simple linear regression is calculated. A slope of 1.0 represents the perfect prediction and any deviation from 1.0 is representative of an error. This procedure was implemented in Matlab (V R2007b).

3.9 Validation in AMS

Once the strength scaling equations were established, they were validated in the AMS. An AnyBody model replicating the experimental setup in the elbow flexion and knee extension postures were developed. As explained in Section 3.4, the same constraints as the test setup were applied to the shoulders, chest, pelvis and upper and lower limbs. Sample upper body and lower body AnyBody models are depicted in Figures 3.5 and 3.6.

Each model is made subject-specific by using the individual anthropometric data including age, gender, body height, body mass and upper and lower segment masses and lengths. Using the latest scaling law (length-mass-fat scaling) as well as the min-max solver, the anthropometry of a particular subject is applied to the model and the peak torque is obtained. The age-gender based strength is calculated from the equation. The hypothesis is that the age-gender strength should be closer to the true measured strength than the length-mass-fat strength. This hypothesis is checked for all subjects in the sample

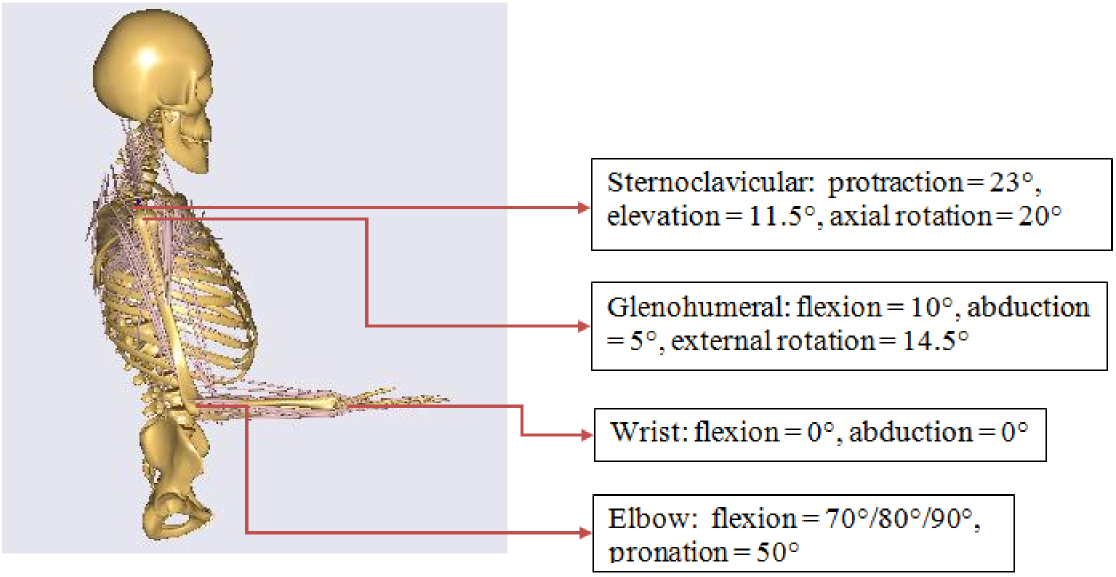


Figure 3.5: An AnyBody model of the upper body replicating the test conditions in terms of posture and physical constraints was developed for validation of the elbow strength scaling laws.

size and for both elbow and knee data. The following questions have to be answered; Is the hypothesis is true? If yes, for how many subjects? What is the improvement of one scaling law over the other?

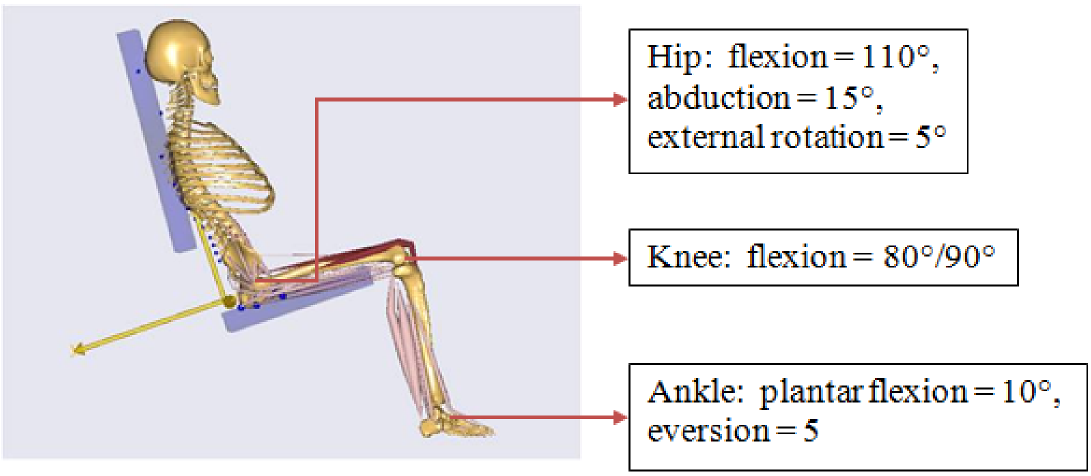


Figure 3.6: An AnyBody model of the full body minus the arms is developed to validate the knee strength scaling laws. The same body posture and boundary conditions as the experimental setup has been replicated.

4 Results

4.1 Physical characteristics

Refer to Table 3.1 for the age group and gender based physical characteristics. Men were significantly taller ($P<0.05$) and heavier ($P<0.05$) than women. The oldest male and female age groups were significantly shorter ($P<0.05$) than both their younger counterparts. There were no significant differences in body mass among either male or female groups.

4.2 Physical activity and pain

The physical activity scores of the participants ranged from 0 to 25003 with an average of 4385($\pm$3724). The percentage of subjects rated as high, moderate and low physically active categories were 59%, 37% and 3%. The correlation coefficient of the test-retest scores of physical activity was very low, at -0.27. A reason for this could be that the data was collected on a subjective basis and not measured, hence not entirely reliable. Also, IPAQ is recommended for the 16-69 age range, but it was also used for the 70-79 range in this study. This may account for such a high tendency toward the high category.

The average pain score on a scale of 0 to 10 was 1.8($\pm$2.0). The test-retest correlation coefficient of pain score was 0.21. However, a closer look into the test-retest scores revealed that 1 subject in particular scored 8 in the first test and 0 in the second round. With the subject's score removed, the correlation coefficient was 0.88. No significant correlation between either pain or physical activity and peak torque was found and are hence not further reported or used in the analysis.

4.3 Upper limb characteristics

The upperarm and forearm lengths and masses are shown in Table 4.1. Masses and lengths of both upper and forearm of males (P<0.05) are significantly higher than females. The oldest male group had significantly lower upperarm mass (P<0.05) and length (P<0.05) than the youngest age group. The same result was found to exist for the females. No significance in forearm length or mass was found to exist for either males or females.

	50–59 yr (50s)	60–69 yr (60s)	70–79 yr (70s)
Male	$n = 40$	$n = 50$	$n = 49$
Upperarm mass, kg	1.59 ± 0.22	1.50 ± 0.26	1.50 ± 0.30*
Upperarm length, cm	20.30 ± 1.80	19.40 ± 2.40	19.00 ± 1.90*
Forearm mass, kg	1.21 ± 0.19	1.19 ± 0.16	1.20 ± 0.20
Forearm length, cm	24.40 ± 1.70	24.30 ± 1.40	24.70 ± 1.80
Female	$n = 42$	$n = 52$	$n = 50$
Upperarm mass, kg	1.40 ± 0.26	1.34 ± 0.19	1.34 ± 0.30*
Upperarm length, cm	18.8 ± 26.0	18.2 ± 20.0	17.8 ± 20.0*
Forearm mass, kg	0.91 ± 0.16	0.89 ± 0.15	0.87 ± 0.18
Forearm length, cm	22.2 ± 12.6	22.2 ± 16.0	22.3 ± 18.0

Table 4.1: Upper limb characteristics: Values are mean(SD); n=number of subjects; *Significantly different from the youngest age group (P<0.05)

4.4 Lower limb characteristics

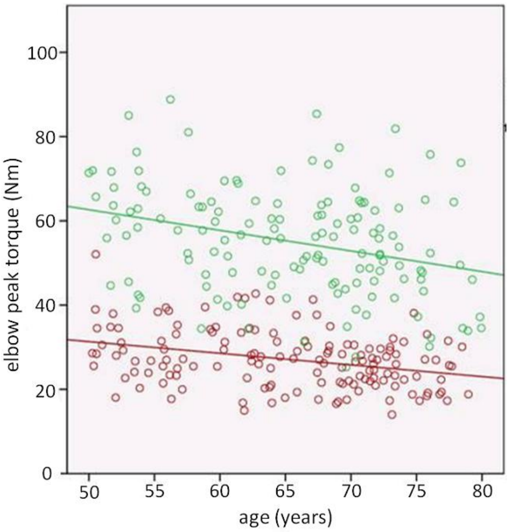
Table 4.2 shows the lengths and masses of the thigh and shank. Males have significantly higher masses (P<0.05) and lengths (P<0.05) of both thigh and shank than females. The oldest male and female age groups have significantly lower thigh mass (P<0.05) and shank mass (P<0.05) than the youngest age group.

	50–59 yr (50s)	60–69 yr (60s)	70–79 yr (70s)
Male	$n = 40$	$n = 50$	$n = 49$
Thigh mass, kg	5.31 ± 1.01	4.86 ± 0.83	4.87 ± 0.98*
Thigh length, cm	25.9 ± 25.0	25.2 ± 30.0	25.4 ± 26.0
Shank mass, kg	3.67 ± 0.59	3.56 ± 0.52	3.38 ± 0.55*
Shank length, cm	39.0 ± 22.0	39.2 ± 20.0	38.4 ± 25.0
Female	$n = 42$	$n = 52$	$n = 50$
Thigh mass, kg	4.82 ± 0.98	4.66 ± 0.97	4.57 ± 0.89*
Thigh length, cm	23.4 ± 24.0	23.6 ± 25.0	23.4 ± 19.0
Shank mass, kg	3.31 ± 0.59	3.17 ± 0.51	3.00 ± 0.58*
Shank length, cm	35.7 ± 23.0	35.9 ± 24.0	35.5 ± 24.0

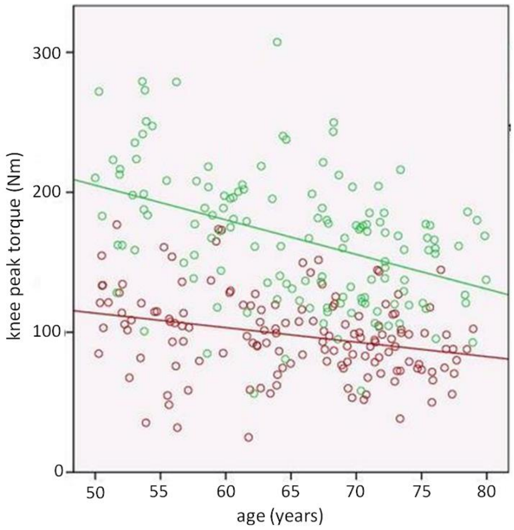
Table 4.2: Lower limb characteristics: Values are Mean(SD); n=number of subjects; *Significantly different from the youngest age group (P<0.05)

4.5 Peak torque

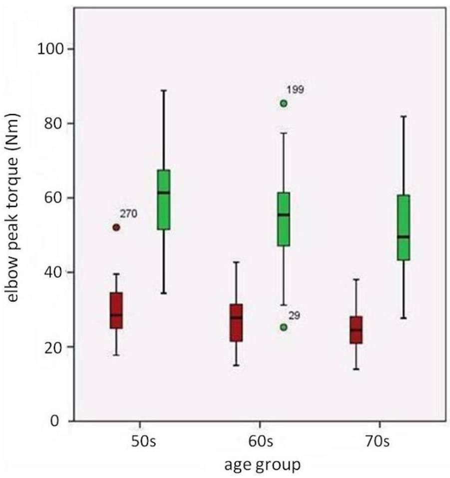
Figure 4.1 graphically presents the change in elbow and knee strength with age as well as the spread of peak torque in the three age groups. Males exhibit a higher decline in both elbow and knee peak torque during their 50s compared to their 60s although the decline of knee peak torque in general is higher compared to elbow peak forque. Females on the other hand have an almost linear decline in elbow peak torque whereas knee peak torque decreases at a slightly higher rate during the 50s decade.



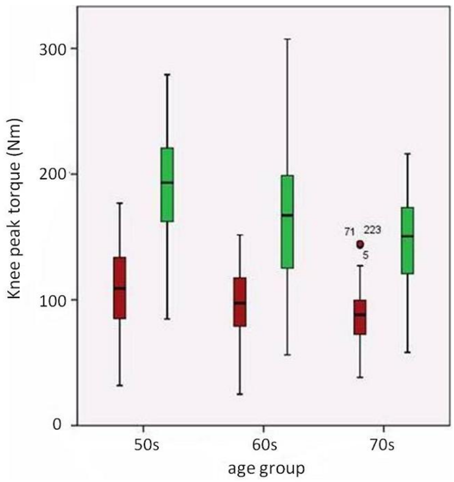
(a) Elbow peak torque (Nm) VS age (years)



(b) Knee peak torque (Nm) VS age (years)



(c) Spread of elbow peak torque over age groups



(d) Spread of knee peak torque over age groups

Figure 4.1: The upper graphs indicate the individual elbow(left) and knee(right) peak torques where the green and red bubbles represent male and female torques respectively overlaid by simple linear regression lines. The lower graphs indicate the spread of the elbow(left) and knee(right) torques in the three age groups i.e. 50s, 60s and 70s

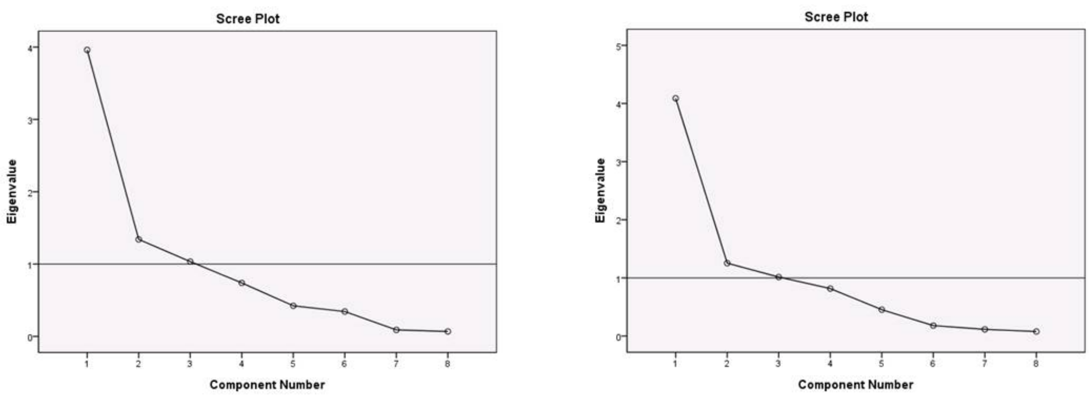
The values of the knee and elbow peak torques as mean($\pm SD$)are presented in Table 4.3. In general, males have significantly higher strength than females across all age groups, and for both elbow and knee strength. The elbow peak torque of the youngest males and youngest females are significantly higher (P<0.05) than the two older age groups. Knee peak torque significantly decreases (P<0.05) across all three age groups, for both genders. The 70 year old males had about 14% lower elbow strength and 24% lower knee strength as compared to the 50 year old males. The 70 year old females had 17% lower elbow strength and 19% lower knee strength as compared to the 50 year old females.

	50–59 yr (50s)	60–69 yr (60s)	70–79 yr (70s)
Male	$n = 40$	$n = 50$	$n = 49$
Elbow peak torque, Nm	60.0 ± 12.6*	54.7 ± 12.3	51.4 ± 12.5
Knee peak torque, Nm	193.3 ± 46.9	165.6 ± 49.1	146.4 ± 32.9**
Female	$n = 42$	$n = 52$	$n = 50$
Elbow peak torque, Nm	29.7 ± 7.0*	27.5 ± 7.4	24.6 ± 5.0
Knee peak torque, Nm	110.0 ± 36.2	96.8 ± 26.2	89.1 ± 23.6**

Table 4.3: Elbow and knee peak torques: Values are Mean(SD); n=number of subjects; *Significantly different from both older age groups (P<0.05); **Each age group is significantly different from the other (P<0.05)

4.6 Factor analysis

As shown in Figure 4.2, factor analysis produces three components with eigenvalues greater than or equal to one. The data are clustered into three sets: the first with gender and lengths explaining circa 50% of the variance; the second factor clusters masses together explaining 16%. Age is the third factor and explains about 12% of the variance in strength. This trend is seen for both the elbow and knee data. For detailed results of the rotated component matrices please refer to A.4



(a) arm strength **(b)** leg strength

Figure 4.2: Scree plots of the results of factor analysis of independent variables for arm(left) and leg(right) strength prediction

4.7 Multiple Linear Regression analysis

Elbow Regression Analysis

MLR using the backward method was first carried out on all the predictors of elbow strength. As shown in Equation 4.1, the dependent variables of elbow peak torque (E_{pt}) in this case were age, gender, body mass, body height, forearm length/mass and upperarm length/mass depicted by A, G, B_m, B_h, FA_l, FA_m, UA_l and UA_m respectively. The explained variance (R^2) was 0.74, five variables had condition indices over a value of 25, and the average VIF was greater than 4. Units of the peak torque, mass, length, age and gender parameters are Nm, kg, cm, years and for gender, female=0 and male=1 respectively.

$$E_{pt} = -27 - 0.24A + 18G - 0.3B_m + 45B_h - 0.7FA_l + 32FA_m - 0.1UA_l + 1.2UA_m \tag{4.1}$$

A deeper look into the data revealed a high correlation between forearm mass and body mass (r=0.82), forearm length and body height (r=0.7) and forearm mass and upperarm mass (r=0.62). Therefore, in successive iterations, it was tried to remove predictors with high mutual correlation. The optimal model was explained by gender (female=0, male=1), forearm mass (kg) and age (years) as shown in Equation 4.2 where the explained variance R^2 is 0.74%.

$$E_{pt} = 26.9 + 21G + 23.4FA_m - 0.32A \tag{4.2}$$

Knee Regression Analysis

In all, there were eight dependent variables to try and define knee peak torque: age, gender, height, body mass, thigh mass, thigh length, shank mass and shank length. MLR using all eight variables results in an equation with an explained variance (R^2) of 0.63 and average variance inflation factor (VIF) greater than 4. In all five variables with condition indices greater than 25 were found. Please refer to Equation 4.3 for the full equation where K_{pt}, A, G, B_m, B_h, T_l, T_m, S_l and S_m are knee peak torque, age, gender, body mass, body height, thigh length, thigh mass, shank length and shank mass respectively. Units of the various predictors are the same as those for the elbow analysis (please refer to previous subsection).

$$K_{pt} = -38 - 1.1A + 60G - 0.8B_m + 148B_h + 0.3T_l + 11T_m - 2.6S_l + 17S_m \tag{4.3}$$

Exploratory multiple linear regression (MLR) using the Backward Method was first investigated. The variables removed were the thigh and shank length. Thigh length has a correlation of $r = 0.62$ with body height, and shank length has $r = 0.82$ with body height. Even with these 2 variables removed, high multicolinearity was found to exist in the model (average variance inflation factor = 3.1). After multiple iterations, it was found that the optimal model of knee peak torque (Nm) was explained by age (year), thigh mass (kg) and gender (female=0, male=1) with an explained variance of 0.61 as shown in Equation 4.4.

$$\text{KPT} = 123.8 + 64.5G + 14.98T_m - 1.47A \tag{4.4}$$

A tabular comparison of the two reduced models are presented in Table 4.4.

	b	SE	Beta	VIF
Upper limb (R^2=0.74)				
Constant	26.90	5.47		
Gender*	21.03	1.44	0.61	1.83
Forearm mass	23.34	3.17	0.31	1.84
Age	−0.32	0.07	−0.15	1.01
Lower limb (R^2=0.60)				
Constant	123.8	20.10		
Gender*	64.5	3.91	0.63	1.03
Thigh mass	14.98	2.07	0.28	1.06
Age	−1.47	0.24	−0.22	1.03

Table 4.4: Reduced Multiple Linear Regression Model: *b*=b-values of regression model; SE=Standard Error; VIF=Variance Inflation Factor; *female=0, male=1

4.8 Cumulative Approximation

The cumulative approximation model was first applied to all predictors of both limbs. The resultant model explained 71.0% and 36.0% variance of the upper and lower limb respectively. The next test was made on the reduced datasets i.e. gender, forearm mass and age in case of the upper limb, and gender thigh mass and age in case of the lower limb. The resultant model explained 72.0% and 36.0% variance of upper and lower limb strength respectively. In each iteration a test was first made to find the optimal blending factor. For complete details of the results, please refer to Tables 4.5 and 4.6 for the upper and lower limb models respectively.

4.9 Statistical validation

Two forms of cross-validation were employed for the MLR models: the two-fold method and the leave-one-out method. More details about these methods have been given in Section 3.8. Please refer to Table 4.7 for the results of 2-fold validation of the upper and lower limb achieved by splitting the dataset into two by random splitting.

The leave-one-out cross-validation was carried out and the resultant predicted torques

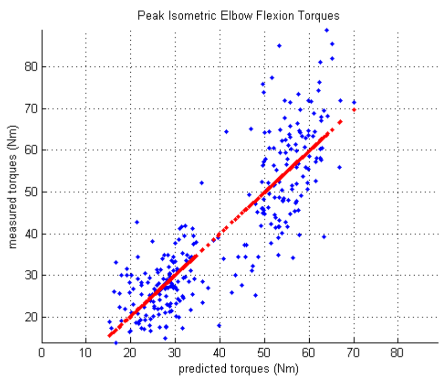
Predictors	n	BF	m	r	R^2
All	283	0.29	1.00	0.83	0.71
	74	0.49	1.00	0.86	0.74
Reduced	283	0.20	1.02	0.84	0.72
	262	0.20	1.01	0.84	0.71

Table 4.5: Cumulative Approximation Model applied to the upper limb. The predictors included in the model are either all 8 predictors i.e. age, gender, body mass, body height, upperarm mass/length and forearm mass/length or a reduced set of only 3 predictors i.e. gender, forearm mass and age. For each set, the model was applied to either all subjects i.e. $n = 283$ or only those subjects whose applicable predictor values fell within the convex hull ($n = 74$ or $n = 262$ for the full and reduced predictor set respectively). *BF*, *m*, r and R^2 are the Blending Factor, slope, correlation coefficient and explained variance respectively.

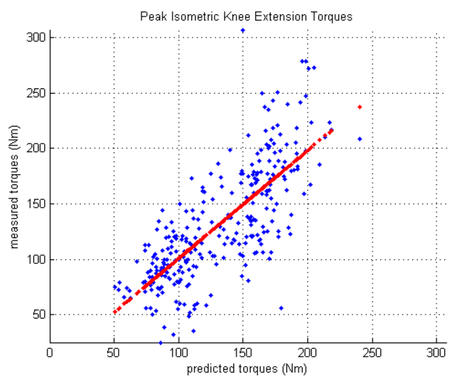
Predictors	n	BF	m	r	R^2
All	283	0.35	1.00	0.60	0.36
	74	0.50	1.00	0.76	0.57
Reduced	283	0.25	1.00	0.60	0.36
	262	0.37	1.00	0.59	0.35

Table 4.6: Cumulative Approximation Model applied to the lower limb. The predictors included in the model are either all 8 predictors i.e. age, gender, body mass, body height, thigh mass/length and shank mass/length or a reduced set of only 3 predictors i.e. gender, thigh mass and age. For each set, the model was applied to either all subjects i.e. $n = 283$ or only those subjects whose applicable predictor values fell within the convex hull ($n = 74$ or $n = 262$ for the full and reduced predictor set respectively). *BF*, *m*, r and R^2 are the Blending Factor, slope, correlation coefficient and explained variance respectively.

are plotted against their corresponding true torques in Figure 4.3. A simple linear regression was performed on the two parameters and the resultant line is superimposed on the same plot.



(a) Elbow peak torque



(b) Knee peak torque

Figure 4.3: Leave-one-out cross validation of the MLR models. Measured peak torques are plotted against predicted torques for all subjects along with the linear regression line. R^2=0.56 for the knee and 0.73 for the elbow

		R^2	R^2 adjusted	Avg VIF
Upper limb				
	Subset1*	0.74	0.73	1.60
	Subset2*	0.74	0.74	1.53
Lower limb				
	Subset1*	0.61	0.60	1.05
	Subset2*	0.60	0.59	1.03

Table 4.7: Data assessment of the MLR models using 2-fold method: R^2 Adj=Adjusted R^2; Avg VIF=Average Variance Inflation Factor; *subsets are each approximately 50% of the full dataset, cases having been randomly selected

4.10 Validation in AMS

The hypothesis of the validation in AMS is that the age-gender strength scaled equations should be closer to the true measured strength than the strength predicted by the AnyBody length-mass-fat scaling law. The questions asked at the beginning of the project were: Is this hypothesis true for the elbow and knee models? If yes, for how many subjects does it hold true? What is the improvement of one scaling law over the other?

From the results of validation, we prove that the hypothesis is true for both elbow and knee models for 74% and 69% of the subjects respectively. The average improvement of the new equation over the old one is 23.8%(21.6) and 15.8%(15.6) for the upper limb and lower limb models respectively. The average improvement of the length-mass-fat equation over the age-gender equation is 5.1%(13.1) for the upper limb model and 8.8%(21.3) for the lower limb model respectively. In terms of knee validation, an attempt to find trends in subjects where the hypothesis failed was made. The findings report that in subjects with low knee peak torque (25 Nm to 85 Nm), low body mass (45 kg to 55 kg), extreme thigh mass (>7 kg and <3 kg) and or very low shank mass (ca. 2 kg) the possibility of a false hypothesis were higher. In terms of elbow validation a trend of low elbow peak torque (< 25 Nm) for false hypotheses was found.

5
Discussion

To briefly summarise our motivation, the AMS today has a number of strength scaling laws based on length, mass and fat percentage. It is well known that strength is also dependent upon age and gender (Akima et al. 2001, Lindle et al. 1997, Pousson et al. 2001, Doriot & Wang 2006, Forrest et al. 2007, Samuel & Rowe 2009, Bemben et al. 1991, Pearson et al. 1985, Rantanen et al. 1997, Viitasalo et al. 1985, Young et al. 1985, Amara et al. 2003, Demura et al. 2010, Frontera et al. 1991, Lin et al. 1996, Miyoshi et al. 2005, Stoll et al. 2000, Stubbs et al. 1993, Sunnerhagen et al. 2000, Kim et al. 2010, Vidt et al. 2012) but there is no agreement on how this strength change occurs with age, between males and females and for different functional muscle groups.

Because AMS has the advantage of being a sophisticated musculoskeletal modeling system, there is a need for its introduction into the ergonomic design and production process of automobiles at Daimler AG. This project is one part of a multi-level cooperation between Daimler AG, Ford-Werke GmbH and BMW AG to develop AMS specifically for the automotive industry. Based on a pilot study by Annegarn et al. (2006) in cooperation with Ford-Werke GmbH it was concluded that age and gender were both important factors to be considered for strength scaling and recommended that the cumulative approximation model produce a better result in terms of explained variance as compared with multiple linear regression. This groundwork has formed the hypothesis of our project.

The major goals achieved are in the following sequence; to collect anthropometric and strength data from an older population, define strength in terms of these predictor values, reduce the strength equations to a set of sufficient and necessary predictors using MLR and CA models, validate these models statistically and in AMS, and finally compare the models.

The main results of the study are that the equations defining strength of our population could be reduced to a set of predictors including gender, forearm mass and age for the upper body that explained almost 74% of the variance. In terms of the lower body, gender, thigh mass and age made up a reduced set explaining 61% of the variance. Contrary to our hypothesis, the CA model did not produce better results in terms of explained variance. The upper body results of the CA model were slightly worse than that of MLR and the explained variance of the lower body was reduced to almost half compared to MLR.

Since the CA results were not up to to our expectation, further analysis and validation was carried out only on the MLR results. A good crossvalidation was statistically achieved. Validation of the new scaling law in AMS compared to the existing length-mass-fat law showed an improvement in performance of circa 20%.

5.1 Strength decline over age

The first conclusive result of our study is that males have greater strength than females. This statement is in agreement with other studies (Lin et al. 1996, Samuel & Rowe 2009, Lynch et al. 1999, Stoll et al. 2000, Xiao et al. 2005, Lindle et al. 1997). In our study, females produced approximately 49% and 59% less knee and elbow torque respectively compared to males. Samuel & Rowe (2009) also reported that the overall isometric knee extensor moment at 90 ° in females aged 60 to 79 years was 59% less than their male counterparts. Xiao et al. (2005) reported that females in his study had mean strengths about 50% lower than that of males. It must be noted that women have a lower lean muscle mass than men (30% versus about 42%). This means that there is essentially no strength difference between genders in terms of the cross-sectional area of muscle (Schantz et al. 1976) since the number of muscle fibres being the same in both genders, males have circa 25% more cross-sectional muscle fibre area than females (Costill et al. 1976).

The overall isometric torque at the elbow and knee decreased by approximately 20% when strength of the 70 year olds was compared to that of the 50 year olds. The decline of isometric peak torque of the knee extensors is significant over all three age groups. The isometric peak torque of the elbow flexors, on the other hand, reduces significantly from the 50s to 60s age group but appears to be better preserved from the 60s to the 70s age groups. In both males and females, upper limb strength appears to decline at a slower rate than lower limb strength. In other words, upper limb strength on the whole appears to be better preserved compared to lower limb strength. This result is in agreement with previous studies by Runnels et al. (2005*b*), Frontera et al. (1991), McDonagh et al. (1984). On the contrary, in a 5 year longitudinal study of men and women from 75 to 80 years, Rantanen et al. (1997) reported that there was a higher decline in maximal isometric elbow flexors compared to the knee extensors.

Looking at pure strength versus age data, the decline in male strength was steeper than that in females for both upper and lower limb. The same was reported by Danneskiold-Samsøe et al. (2009). Stoll et al. (2000) on the other hand reported the contrary in the decline of strength in multiple functional muscle groups of adults above ca. 50 years of age.

5.2 Predictors of strength

Factor analysis clusters the data into three sets: the first with gender and lengths explaining about 50% of the variance; the second factor clusters masses together, explaining 16%. Age is the third factor and explains about 12% of the variance in strength. This trend is seen for both the elbow and knee data. The resultant MLR produces equations consistent with the findings of factor analysis i.e. gender, one segment mass and age are the three variables explaining 74% and 60% of elbow and knee peak torques respectively. Lin et al. (1996) performed MLR on various types of lifting strengths and concluded that gender, age and body mass are important predictors of arm and leg strength and explain between 63% and 72% of the population variance. Our results follow a similar trend where gender is the most important factor of the MLR analysis. Also gender, segment mass and age explain 61% and 74% lower and upper body strength respectively. The b-coefficients of gender and age of both extremities coincide greatly in both studies. Chaffin et al. (1978) also found that gender, age, body weight and stature could predict static lifting strengths of the arm, back and leg.

5.3 Pain and physical activity

Although it is well established that there is a correlation between physical activity and strength (Volkers et al. 2012, Tolea et al. 2012, Shephard 2008, Amara et al. 2003), the actual measurement of fitness level was out of the scope of our study. Therefore in order to gain a better understanding of the participants, it was decided to obtain the level of physical activity on a subjective basis using the IPAQ questionnaire. The IPAQ was sectioned into the domains leisure time, domestic, work-related and transport related physical activities. Each subject was accordingly scored and then categorized into the low, moderate or high activity category. The spread of the actual scores were quite high. Only 3% of the sample fell into the low category. Although IPAQ is recommended for the 16-69 age range, it was also used for the 70-79 range in this study. This may account for such a high tendency toward the high category. The overall pain of the sample was relatively low, with only 4% of the subjects rating their overall pain over 6 on a scale of 0 to 10.

5.4 Segment mass calculation

The calculation of segment masses is based on an estimation of density as 1.06 gm/cc. This is of course only an estimation and not a true reflection considering the fact that a large percentage of today's population is overweight (WHO Technical Report Series 2000), and fat has a lower density than muscle. A better option would be to use hydrostatic weighing.

This would have been feasible for the upper limb (using a tube of water for immersion), but rather impractical and unsafe for the lower limb considering the age range of our subjects. In addition such a protocol is time consuming considering our large sample base. In the work done at the University of Maastricht, the arm and forearm masses were measured using the hydrostatic method, and the thigh and shank masses were calculated by manually measuring the girths and lengths of the thigh and shank at three specific points per segment. We decided to use the same protocol for both upper and lower limbs in order to bring about the same accuracy, or error, into the model. MRI scanning would be a better method but is costly and time consuming.

5.5 Multiple Linear Regression of upper limb

As given in its name, Multiple Linear Regression assumes a linearity in the relationship between predictor and strength variables. Although MLR has been successfully used in various studies Lynch et al. (1999), Frontera et al. (2000), Anderson et al. (2007), it is well known that there is a non-linearity in the relation between strength and age and gender. This non-linearity is more prevalent when assuming the entire adult life-span i.e. 20 to 80 years. In our study, we zoom into the 50 to 80 year group. This can allow us to possibly reduce the problem of non-linearity and thereby possibly prevent great errors in strength prediction. An advantage of MLR is that it makes it possible to extrapolate data.
Table 4.4 shows the results of MLR of the upper limb model. Age, gender and forearm mass variables are the best predictors of peak elbow torque and explain up to 75% of the torque variance (R^2=0.75). The adjusted R^2 is only 1% lesser in value indicating good cross-validity of the model. The average VIF however is 1.56 which may be cause for concern. Durban-Watson statistic is 1.8 and hence the assumption of independent errors can be established. Comparing these results with MLR using all eight independent variables, the explained variance would have increased only marginally but like in the case of the lower limb data, produced a much higher VIF which is due to high correlations between mass parameters and length parameters.

5.6 Multiple Linear Regression of lower limb

Refer to Table 4.4 for the results of MLR analysis for the knee torque. Age, gender and thigh mass have been selected to be the best combination of dependent variables and explain 60% of the variation in peak knee torque (R^2=0.60). Adjusted R^2 is 0.59 which is only 1% less than R^2, indicating that the cross-validity of this model is good. The average variance inflation factor (VIF) is 1.04 i.e. very close to 1 which indicates that collinearity is not a problem for this model. The Durban-Watson statistic is 1.9 i.e. very close to 2 so that the assumption of independent errors has been met.
Had we used all eight predictors in our model, the values of R^2 would have increased to 0.63 implying that these extra five predictors would have explained only 3% more of the

knee peak torque variation. Moreover, the average VIF would have increased to 4.13 indicating very high multicollinearity in the model. A high correlation between body mass and lower limb volumes has also been found in a study conducted by Correa & Pandy (2011). In our study, the calculation of segment mass is but a multiplication of calculated segment volume by a factor of density (1.06 gm/cc). In this study, it is found that even though similar parameters are found to best describe strength, still, the lower limb model explains about 15% less strength than the upper limb model. One reason for this phenomenon could be that our quadriceps muscles are the largest in the body. The lower limb muscles in general are involved in regular physical activity such as walking, climbing stairs etc over age compared to the upper limb muscles. This could mean that there may be another rather important variable, physical activity, needed to explain the change in lower limb strength over age (Amara et al. 2003). Measurement and quantification of physical activity is quite a huge undertaking and was out of the scope of this study. We attempted to obtain an idea of physical activity of our participants, but we believe that because it was a subjective measure it was therefore not entirely reliable.

5.7 Cumulative Approximation

A major result of this study is that the cumulative approximation method, contrary to the hypothesis, did not produce a better strength prediction compared to MLR. Since this was the case, there was no real reason to continue a validation or further investigation into CA since MLR has the advantage of simplicity and can, to some extent, also extrapolate data. Besides CA having the inability to extrapolate data, another possible reason for its low performance could be due to the high dimensionality of the data.

5.8 Validation

Looking at the assessment models in Table 4.7, the values of R^2, adjusted R^2 and average VIF are almost identical to the actual model. The leave-one-out method produces an explained variance thereby indicating a good cross-validation. To assess our final lower limb model, the data set was randomly split by approximately half. MLR was performed on each half and the results compared with the actual model as shown in Table 4.7. The values of R^2, adjusted R^2 and average VIF are almost identical to the actual model which validates the model. The leave-one-out method of cross-validation produces an explained variance lower by 4%. The age-gender scaling law was implemented in AMS and compared with the existing length-mass-fat law. The new law improved the prediction by almost 20% for more than two-thirds of the subject population.

6 Conclusion

The world today is looking at a drastic demographic change where a significant population rise is coupled with a decreased birth rate and an increased life expectancy. The result is an ever increasing proportion of males and females aged 60 and above. The physiological effects of aging can be summarized into an overall decline in strength and flexibility of the body. There is an ever increasing demand by older generations for new and improved technologies to provide support in terms of design and evaluation of safe and comfortable environments for work and activities of daily living.

Various digital modelling tools are available today to help reduce the time and costs for the development of such environments by allowing for quick testing and evaluation. The Anybody Modelling System™ or AMS offers the advantage of being a programmable biomechanical simulation software based on inverse kinematics where muscles are used to drive the bones. This model is strength scalable but lacks the input of age and gender and muscle groups in its scaling laws. Although it is a well known fact that age and gender are important contributors of strength prediction, there is no clear consensus on the decline between gender, muscle groups, type of strength and speed of measurement.

This study was set out to provide a database of anthropometry and isometric peak torques of the elbow and knee representing the male and female population aged 50 to 80 years from the Munich area of Germany. The effects of age, gender, body height, body mass, segment length and segment mass on the maximal voluntary isometric contraction of the knee extensors and elbow flexors were investigated. Based on the results of an initial study at the University of Maastricht in 2007, the methods of MLR and CA were used to establish an elbow and knee model. In addition, this study aimed to condense the models into a set of sufficient and necessary predictors by removing redundancies based on multicollinearity.

A full body scan using laser technology was used to obtain anthropometric data including segment lengths. Segment masses were calculated from segment lengths and circumferences by assuming a fixed value of body density. This is a shortcoming of the research study since it is known that bone, muscle and fat tissue have different densities. Peak voluntary isometric torque of the right elbow flexors and right knee extensors was measured using the Isomed 2000 dynamometer. The hypotheses of this study were:

Hypothesis 1: Age and gender are important and necessary strength predictors

A major finding of this study supports the basic research hypothesis that using MLR, it was possible to reduce the predictors of PT from eight variables to three including gender, one segment mass and age. This finding coincides with the results of factor analysis where it was found that the strength predictors could be clustered into three sets of data; gender and lengths were the first cluster explaining 50% of the variance. Then came segment and body masses explaining 16% and thirdly age with a 12% explanation of variance. The segment mass in the final reduced equation was forearm mass in case of the upper body, and thigh mass in case of the lower body. The elbow model explained 74% of the variance whereas the knee model explained 61%. The explained variance for the full predictor set was similar to the reduced predictor set. This proves that the reduced set reduced multicollinearity and removed redundancies in the statistical models. A possible reason for the remaining unexplained strength, especially in the lower body, could lie in the fact that physical activity has not been included as a possible strength predictor. Although the level of fitness is well established as an important measure of strength, this variable has been omitted from the study as an objective measure since it falls outside the scope of the project. Various forms of validation of the elbow and knee models in MLR were employed including two-fold and leave-one-out methods. Both methods established a high degree of cross-validation in both models.

Hypothesis 2: CA performs better than MLR

The second important result of this study is that contrary to the initial hypothesis, CA did not produce a more accurate prediction of strength compared to MLR. The explained variance of the CA model compared to MLR was slightly lower for the upper body but about 40% less for the lower body. Given that MLR performed much better than CA, a decision was made after analysis not to continue with either statistical cross-validation of the CA model or any further implementation in AMS.

Hypothesis 3: Age-gender scaling law has better accuracy in AMS than available scaling laws

The answer to the third hypothesis is that the age-gender strength scaling laws provided a much more accurate strength than the existing scaling laws in AMS ranging from just a few percent to as high as 45%. Instances where the law failed to perform were in case of outliers such as extremely low peak torque, low body mass, low shank mass and/or extremely high thigh mass. These factors should be kept in mind when using the age-gender scaling laws for further predictions in AMS.

Recommendations

The next step of this study is to submit this thesis to AMS as proof material that the age-gender scaling laws do bring about a considerate increase in performance to justify that time and other resources are invested by the software developers to incorporate these laws into the AnyBody software. One should bear in mind, that a strong feature of AMS is that the user is allowed the freedom to select from a range of scaling laws starting with a rudimentary no-scaling law introduced into the system at its inception. A great advantage is that many AMS users, from different backgrounds, can have the opportunity to test the scaling law and provide feedback and possible improvements.

Although forearm mass and thigh mass have proven to be important predictors of strength alongside age and gender, it may not always be feasible to measure a person's individual segment mass in the case of everyday testing. Therefore a more practical substitute such as body mass should be considered but this presents a tradeoff since, in our model, the use of body mass decreases the explained variance by approximately 5% for either model.

This study has produced an extensive database of anthropometry of males and females aged 50 to 80 years. The data analysis has incorporated only a few parameters such as body height, segment lengths and segment masses. In addition, levels of physical activity of the participants have also been quantified based on questionnaires. An interesting project using the data already acquired may be to further investigate any correlations between levels of physical activity and anthropometric parameters such as hip-waist ratio, body mass index and waist girth.

Referring to Section 3.6, each trial was filtered and an absolute maxima over a 20 msec moving average bin found. The peak isometric elbow or knee torque of a particular participant was the highest peak torque within all relevant trials. The peak torques during the experiments have been noted down and care has been taken to ensure that these values have stayed within a 10% tolerance band. Another approach worth investigating may be to calculate the peak torque as the average of all relevant trials of a given subject instead.

As mentioned in Section 3.4, isokinetic torque of the elbow and knee flexors and extensors of all subjects have also been recorded in order to carry on further investigations independent of this project. Besides analysis of the isokinetic data, development of separate age-gender based strength scaling equations and application in AMS are also of great interest.

A useful project for the future could be to compare the accuracies of segment mass measurement using different methods i.e. body scanner, commercial scales, hydrostatic weighing and MRI. It is important to have an estimate of how much accuracy (or error) each measurement scheme introduces to the methodology. As an additional validation, the anthropometric and strength data could also be acquired from the participants recruited in this study, the age-gender scaling laws established, and the accuracy of the predicted strengths between methods of segment mass measurement compared.

To improve the prediction rate, a more in depth and objective measure of physical activity is also recommended. The development of a quick and easy fitness "measure" for the older population could also be a worthwhile spin-off project. Given the high incidence of obesity in today's population, a comparison of muscle-fat distribution between obese and normal subjects, not just in the torso region, but also in the extremities, using MRI could be worth further investigation.

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A

Appendix

A.1 Test-retest reliability scores

Eight subjects were tested a second time after a one week interval by the same investigator and using the same protocol in order to determine the reliability of our test design and equipment. Table A.1 shows Pearson's correlation coefficient of the measured and calculated parameters.

A test-retest study was performed to determine the reliability of our apparatus and experiment protocol. Eight subjects were tested twice with a one week interval.

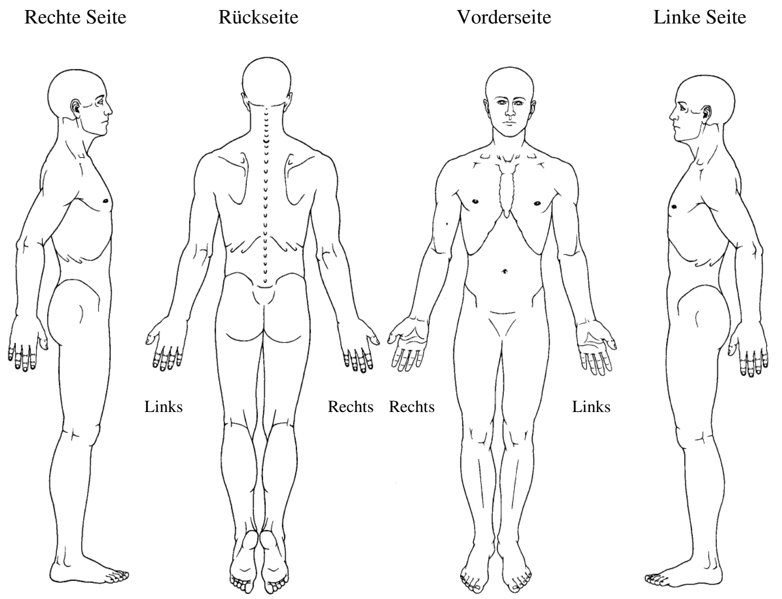
Parameter	r
elbow peak torque	0.95
knee peak torque	0.98
upperarm length	0.72
upperarm mass	0.65
forearm length	0.74
forearm mass	0.93
thigh length	0.89
thigh mass	0.89
shank length	0.88
shank mass	0.94

Table A.1: Test-retest reliability results: Pearson's correlation coefficient (r) calculated for torque, length and mass parameters for 8 subjects

A.2 Pain questionnaire

Schmerzfragebogen

1. Bitte markieren Sie mit „x“ die Stelle, die Sie schmerzt:



2. Kreisen Sie die Zahl ein, die Ihre durchschnittlichen Schmerzen in den vergangenen 7 Tage am besten beschreibt:

0 **kein Schmerz**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10** **stärkste vorstellbare Schmerzen**

Figure A.1: Pain Questionnaire: In part I, the subject marks where on the body he is experiencing pain. In part II, overall pain over the past 7 days has to be quantified between 0 and 10 with 0 being no pain and 10 being worst imaginable pain.

A.3 Physical activity questionnaire

The International Physical Activity Questionnaire or IPAQ is an open access questionnaire, publically available, and requires no permission to be used. It is available in two formats: the long format and the short version. A great advantage is that emphasis has been placed to make the IPAQ culturally adaptable in terms of conceptual, metric and linguistic equivalence. It is available today in over twenty languages. This study makes uses of the Austrian long version, written in German.

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE (Oktober 2002)

SELBSTAUSFÜLLER LANG-VERSION FÜR DIE VERGANGENEN 7 TAGE

ZU VERWENDEN FÜR JUNGENDLICHE UND ERWACHSENE IM MITTLEREN ALTER (15-69 Jahre)

Der International Physical Activity Questionnaire (IPAQ) umfasst eine Zusammenstellung aus 4 Fragebögen. Lange (5 Aktivitätsbereiche unabhängig voneinander befragt) und kurze (4 allgemeine Items) Versionen für die Durchführung von Telefonbefragungen als auch für die selbst zu verwaltende Methode sind verfügbar. Die Absicht der Questionaires ist es einfache Instrumente zur Verfügung zu stellen, die verwendet werden können um international vergleichbare Daten für die gesundheitsfördernde physische Aktivität zu erhalten.

Hintergrund des IPAQ
Die Entwicklung eines internationalen Messinstruments zur Erhebung der physischen Aktivität begann in Genf im Jahr 1998 und wurde im Jahr 2000 durch extensive Reliabilitäts- und Validitätststests in 12 unterschiedlichen Ländern (14 Orte) fortgesetzt. Vom Endergebnis wird behauptet, dass es annehmbare Messeigenschaften für den Einsatz an vielen Orten und in unterschiedlichen Sprachen besitzt und es geeignet ist für landesweite bevölkerungsbezogene Untersuchungen für die Prävalenz der Partizipation in physischer Aktivität.

Verwendung des IPAQ
Es wird empfohlen die IPAQ-Instrumente für Untersuchungen und für Forschungszwecke zu verwenden. Die Anordnung der Fragen sowie die Satzstellungen sollten möglichst unverändert bleiben um die psychometrischen Eigenschaften des Instruments nicht zu beeinflussen.

Übersetzung vom Englischen und kulturelle Anpassung
Übersetzungen aus dem Englischen werden angestrebt um die weltweite Verwendung des IPAQ zu erleichtern. Informationen über die Verfügbarkeit des IPAQ in unterschiedlichen Sprachen können unter www.ipaq.ki.se abgerufen werden. Sollte eine neue Übersetzung vorgenommen werden wird die Verwendung der auf der IPAQ-Website beschriebenen Rückübersetzungsmethoden unbedingt empfohlen. Wenn möglich ziehen sie bitte in Erwägung ihre Übersetzung des IPAQ für andere auf der IPAQ-Website zugänglich zu machen. Weitere Details über Übersetzungen und kulturelle Adaptationen können von der Website gedownloadet werden.

Weitere Entwicklungen des IPAQ
Die internationale Zusammenarbeit beim IPAQ geht weiter und die ***International Physical Activity*** Studie ist in der Entwicklungsphase. Für weitere Informationen steht die IPAQ-Website zur Verfügung.

Weitere Informationen
Detaillierte Informationen über Forschungsmethoden die in der Entwicklung der IPAQ-Instrumente verwendet werden finden Sie unter www.ipaq.ki.se oder bei Booth, M.L. (2000). *Assessment of Physical Activity: An International Perspective.* Research Quarterly for Exercise and Sport, 71 (2): s114-20. Weitere wissenschaftliche Publikationen und Präsentationen über die Anwendung des IPAQ sind auf der Website zusammengefasst.

INTERNATIONAL PHYSICAL ACTIVITY QUESTIONNAIRE

Wir sind daran interessiert herauszufinden welche Arten von körperlichen Aktivitäten Menschen in ihrem alltäglichen Leben vollziehen. Die Befragung bezieht sich auf die Zeit die Sie während der **letzten 7** Tage in körperlicher Aktivität verbracht haben. Bitte beantworten Sie alle Fragen (auch wenn Sie sich selbst nicht als aktive Person ansehen). Bitte berücksichtigen Sie die Aktivitäten im Rahmen Ihrer Arbeit, in Haus und Garten, um von einem Ort zum anderen zu kommen und in Ihrer Freizeit für Erholung, Leibesübungen und Sport.

Denken Sie an all Ihre **anstrengenden** und **moderaten** Aktivitäten in den **vergangenen 7 Tagen**. **Anstrengende** Aktivitäten bezeichnen Aktivitäten die starke körperliche Anstrengungen erfordern und bei denen Sie deutlich stärker atmen als normal. **Moderate** Aktivitäten bezeichnen Aktivitäten mit moderater körperlicher Anstrengung bei denen Sie ein wenig stärker atmen als normal.

TEIL 1: KÖRPERLICHE AKTIVITÄT AM ARBEITSPLATZ

Im ersten Abschnitt geht es um Ihre Arbeit. Das beinhaltet bezahlte Arbeit, Landwirtschaft, freiwillige Tätigkeiten, Seminare und alle anderen unbezahlten Tätigkeiten die Sie außerhalb von zuhause verrichtet haben. Geben Sie hier keine unbezahlten Tätigkeiten an die Sie zuhause verrichtet haben, wie Arbeiten in Haus und Garten, anfallende Instandhaltungsarbeiten und Sorgen für die Familie. Dies wird in Abschnitt 3 befragt.

1. Haben Sie momentan einen Job oder verrichten Sie irgendwelche unbezahlte Arbeiten außerhalb von zuhause?

☐ Ja

☐ Nein → ***Springen Sie weiter zu Teil 2: BEFÖRDERUNG***

Die folgenden Fragen sind über die körperliche Aktivität in den **vergangenen 7** Tagen im Rahmen Ihrer bezahlten und unbezahlten Arbeit. Dies beinhaltet keine Wegstrecken zur oder von der Arbeit.

2. An wie vielen der **vergangenen 7 Tage** haben Sie anstrengende körperliche Aktivitäten wie schweres Heben, Graben, schwere Bauarbeit oder Stiegensteigen **im Rahmen Ihrer Arbeit** verrichtet? Denken Sie dabei nur an körperliche Aktivitäten die Sie für mindestens 10 Minuten ohne Unterbrechung verrichtet haben.

_____ **Tage pro Woche**

☐ Keine anstrengenden körperlichen Aktivitäten im Rahmen der Arbeit
→ **Springen Sie weiter zu Frage 4**

3. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit **anstrengender** körperlicher Aktivität im Rahmen ihrer Arbeit verbracht?

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

4. Denken Sie erneut nur an die körperlichen Aktivitäten die Sie für mindestens 10 Minuten ohne Unterbrechung verrichtet haben. An wie vielen der **vergangenen 7 Tage** haben Sie moderate körperliche Aktivitäten wie Tragen leichter Lasten **im Rahmen Ihrer Arbeit** verrichtet? Fußwegstrecken bitte nicht mit einbeziehen.

_____ **Tage pro Woche**

☐ Keine moderaten körperlichen Aktivitäten im Rahmen der Arbeit

→ **Springen Sie weiter zu Frage 6**

5. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit moderater körperlicher Aktivität im Rahmen Ihrer Arbeit verbracht?

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

6. An wie vielen der **vergangenen 7 Tage** haben Sie **Fußwegstrecken** von mindestens 10 Minuten ohne Unterbrechung im Rahmen Ihrer Arbeit zurückgelegt? Bitte keine Wegstrecken zur oder von der Arbeit mit einbeziehen.

_____ **Tage pro Woche**

☐ Keine Fußwegstrecken im Rahmen der Arbeit
→ ***Springen Sie weiter zu Teil 2: BEFÖRDERUNG***

7. Wie viel Zeit haben Sie an einem dieser Tage für gewöhnlich mit **Wegstrecken** im Rahmen Ihrer Arbeit verbracht?

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

Teil 2: KÖRPERLICHE AKTIVITÄT ZUR BEFÖRDERUNG

In diesen Fragen geht es um die Fortbewegungen von einem Ort zum anderen, wie die Wege zu Arbeit, Geschäften, Kino, usw.

8. An wie vielen der **vergangenen 7 Tage** sind Sie mit einem **motorisierten Verkehrsmittel** wie Zug, Bus, Auto oder Straßenbahn **gefahren**?

_____ **Tage pro Woche**

☐ Keine Fahrten in motorisierten Verkehrsmitteln
→ ***Springen Sie weiter zu Frage 10***

9. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit **Fahrten** in Zug, Bus, Auto, Straßenbahn oder irgendeinem motorisierten Verkehrsmittel verbracht?

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

Denken Sie jetzt nur an das **Fahrradfahren** und **zu Fuß Gehen**, bei dem Sie für Wege zur und von der Arbeit, für Botenwege, sowie für Wegstrecken um von einem Ort zum anderen zurückgelegt haben.

10. An wie vielen der **vergangenen 7 Tage** sind Sie für mindestens 10 Minuten ohne Unterbrechung **fahrradgefahren** um **von einem Ort zum anderen** zu gelangen?

_____ **Tage pro Woche**

☐ Kein Fahrradfahren von einem Ort zum anderen
→ ***Springen Sie weiter zu Frage 12***

11. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage für das **Fahrradfahren** von einem Ort zum anderen verwendet??

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

12. An wie vielen der **vergangenen 7 Tage** sind Sie für mindestens 10 Minuten ohne Unterbrechung **zu Fuß gegangen** um **von einem Ort zum anderen** zu gelangen?

_____ **Tage pro Woche**

☐ Kein zu Fuß Gehen von einem Ort zum anderen
→ ***Springen Sie weiter zu Teil 3: HAUSARBEIT, HAUSINSTANDHALTUNG UND SORGEN FÜR DIE FAMILIE***

13. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage für das **zu Fuß Gehen** von einem Ort zum anderen verwendet?

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

TEIL 3: HAUSARBEIT, HAUSINSTANDHALTUNG UND SORGEN FÜR DIE FAMILIE

In diesem Abschnitt geht es um körperliche Aktivitäten die Sie in den **vergangen 7 Tagen** in und um ihr Haus verrichtet haben, wie Hausarbeit, Arbeiten in Hof und Garten, Instandhaltungsarbeiten und Sorgen für die Familie.

14. Denken Sie nur an die körperlichen Aktivitäten die Sie für mindestens 10 Minuten ohne Unterbrechung verrichtet haben. An wie vielen der **vergangenen 7 Tage** haben Sie anstrengende körperliche Aktivitäten wie Tragen schwerer Lasten, Holzhaken, Schneeschaufeln oder Graben **im Hof oder im Garten** verrichtet?

    _____ **Tage pro Woche**

    ☐ Keine anstrengenden körperlichen Aktivitäten im Hof oder im Garten
    → ***Springen Sie weiter zu Frage 16***

15. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit **anstrengender** Aktivität in Garten und Hof verbracht?

    _____ **Stunden pro Tag**
    _____ **Minuten pro Tag**

16. Denken Sie erneut nur an die körperlichen Aktivitäten die Sie für mindestens 10 Minuten ohne Unterbrechung verrichtet haben. An wie vielen der **vergangenen 7 Tage** haben Sie moderate Aktivitäten wie Tragen leichter Lasten, Fegen, Fensterputzen und Rechen **im Hof oder im Garten** verrichtet?

    _____ **Tage pro Woche**

    ☐ Keine moderate Aktivität im Garten oder im Hof
    → ***Springen Sie weiter zu Frage 18***

17. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit **moderater** körperlicher Aktivität im Garten oder im Hof verbracht?

    _____ **Stunden pro Tag**
    _____ **Minuten pro Tag**

18. Denken Sie erneut nur an die körperlichen Aktivitäten die Sie für mindestens 10 Minuten ohne Unterbrechung verrichtet haben. An wie vielen der **vergangenen 7 Tage** haben Sie moderate Aktivitäten wie Tragen leichter Lasten, Fensterputzen, Bodenaufwaschen und Fegen **zuhause** verrichtet?

    _____ **Tage pro Woche**

    ☐ Keine moderaten Aktivitäten zuhause
    → ***Springen Sie weiter zu Teil 4: KÖRPERLICHE AKTIVITÄTEN IN ERHOLUNG, SPORT UND FREIZEIT***

19. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit **moderaten** körperlichen Aktivitäten zuhause verbracht?

    _____ **Stunden pro Tag**
    _____ **Minuten pro Tag**

TEIL 4: KÖRPERLICHE AKTIVITÄTEN IN ERHOLUNG; SPORT UND FREIZEIT

In diesem Abschnitt geht es um alle körperlichen Aktivitäten die Sie in den **vergangenen 7 Tagen** ausschließlich in Erholung, Sport, Leibesübungen und Freizeit verrichtet haben. Bitte keine Aktivitäten mit einbeziehen die Sie bereits angegeben haben.

20. Ohne die Fußwege die Sie bereits genannt haben, an wie vielen der **vergangenen 7 Tage** sind Sie in ihrer **Freizeit** für mindestens 10 Minuten ohne Unterbrechung **zu Fuß** gegangen?

_____ **Tage pro Woche**

☐ Kein zu Fuß gehen in der Freizeit
➡ ***Springen Sie weiter zu Frage 22***

21. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit **zu Fuß Gehen** in ihrer Freizeit verbracht?

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

22. Denken sie nur an die körperlichen Aktivitäten die Sie für mindestens 10 Minuten ohne Unterbrechung verrichtet haben. An wie vielen der **vergangenen 7 Tage** haben Sie **anstrengende** körperliche Aktivitäten wie Aerobic, Laufen, schnelles Fahrradfahren oder schnelles Schwimmen in ihrer **Freizeit** verrichtet?

_____ **Tage pro Woche**

☐ Keine anstrengenden Aktivitäten in der Freizeit
➡ ***Springen Sie weiter zu Frage 24***

23. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit **anstrengender** körperlicher Aktivität in ihrer Freizeit verbracht?

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

24. Denken Sie erneut nur an die körperlichen Aktivitäten die Sie für mindestens 10 Minuten ohne Unterbrechung verrichtet haben. An wie vielen der **vergangenen 7 Tage** haben sie **moderate** körperliche Aktivitäten wie Fahrradfahren bei gewöhnlicher Geschwindigkeit, Schwimmen bei gewöhnlicher Geschwindigkeit und Doppel-Tennis in ihrer **Freizeit** verrichtet?

_____ **Tage pro Woche**

☐ Keine moderaten Aktivitäten in der Freizeit
➡ ***Springen Sie weiter zu Teil 5: IM SITZEN VERBRACHTE ZEIT***

25. Wie viel Zeit haben Sie für gewöhnlich an einem dieser Tage mit **moderater** körperlicher Aktivität in ihrer Freizeit verbracht?

_____ **Stunden pro Tag**
_____ **Minuten pro Tag**

TEIL 5: IM SITZEN VERBRACHTE ZEIT

Bei den letzten Fragen geht es um die Zeit die Sie bei der Arbeit, zuhause, bei Seminaren und in der Freizeit in Sitzen verbracht haben. Dies kann Zeit beinhalten wie Sitzen am Schreibtisch, Besuchen von Freunden und vor dem Fernseher sitzen oder liegen. Keine Zeit für Sitzen in einem motorisierten Verkehrsmittel mit einbeziehen von der Sie mir bereits erzählt haben.

26. Wie viel Zeit haben Sie in den **vergangenen 7 Tagen** mit **Sitzen** an **Wochentagen** verbracht?

    _____ **Stunden pro Tag**
    _____ **Minuten pro Tag**

27. Wie viel Zeit haben Sie an den **vergangenen 7 Tagen** mit **Sitzen** an **Wochenendtagen** verbracht?

    _____ **Stunden pro Tag**
    _____ **Minuten pro Tags**

Das ist das Ende der Befragung, danke für Ihre Teilnahme.

A.4 Factor analysis: rotated component matrices

Component	1	2	3
age			−0.799
gender	0.775	0.326	
body height(m)	0.786	0.390	
body mass(kg)		0.914	
upperarm length(cm)	0.561		0.684
upperarm mass(kg)		0.737	0.382
forearm length(cm)	0.840		
forearm mass(kg)	0.535	0.793	

Table A.2: Factor analysis: Rotated component matrix of the arm

Component	1	2	3
age			0.876
gender	0.741		
body height(m)	0.833	0.432	
body mass(kg)		0.898	
thigh length(cm)	0.793		
thigh mass(kg)		0.752	
shank length(cm)	0.804	0.330	
shank mass(kg)		0.916	

Table A.3: Factor analysis: Rotated component matrix of the leg