DEPARTMENT OF HEALTH AND HUMAN SERVICES

Public Health Service
Centers for Disease Control
and Prevention (CDC)

Memorandum

Date: April 12, 2001

From: Roy M. Fleming, Sc.D., Director, Research Grants Program RMF
Office of Extramural Programs, NIOSH, D30

Subject: Final Report Submitted for Entry into NTIS for Grant 5 R03 OH003336-02.

To: William D. Bennett
Data Systems Team, Information Resources Branch, EID, NIOSH, P03/C18

The attached final report has been received from the principal investigator on the subject NIOSH grant. If this document is forwarded to the National Technical Information Service, please let us know when a document number is known so that we can inform anyone who inquires about this final report.

Any publications that are included with this report are highlighted on the list below.

Attachment
cc: Sherri Diana, EID, P03/C13

List of Publications

Vasta PJ, Kondraske GV: An Approach to Estimating Performance Capacity Envelopes: Knee Extensor System Example. Proceedings of the 19th Annual Engineering in Medicine and Biology Society Conference, pp. 1713-1716, 1997

Title: Musculoskeletal Performance Capacity Envelope Estimation

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Abstract:
The purpose of this study was to develop and evaluate an approach to modeling multidimensional (strength, joint angle, and speed) performance capacity envelopes (PCE) that more completely characterize specific human musculoskeletal subsystems (e.g., trunk extensor, wrist extensor). This is a logical extension to the typical two-dimensional families of curves produced by isokinetic measures, which provide only limited utility.

Isometric and new modified isokinetic protocols were used to obtain a parametric data set for each of 35 healthy volunteers, using the knee extensor as a representative subsystem for the approach. Using data for 21 subjects (Phase I of data collection), the functional form of a normalized three dimensional performance capacity envelope representing the general population was determined using statistical analysis of the subject data. A limited subset of each subject's data was then used in combination with the general population model to derive higher-fidelity subject-specific models (i.e., mathematical representations of the three-dimensional performance capacity envelopes. The estimated knee extensor torque capacity of each model was compared to the measured torque values. The approach provided torque capacity estimates that were comparable to test-retest accuracy. The analysis was repeated using data from an additional 14 subjects (Phase II of data collection). While the general model used to derive subject specific models was derived from the Phase I subjects, prediction accuracy was again generally comparable to test-retest accuracy.

It is concluded that the PCE approach is a convenient and concise way to represent the performance capacity of the knee extensor system. More specifically, experimental results demonstrate that it is possible to obtain a fidelity for representation of the entire envelope for a particular individual that is essentially equivalent to that obtained by making a large number of measurements that sample the PCE surface by using a General Population Model that captures the shape of the envelope and a small set of direct measurements that scales or warps the shape model appropriately.

Publications

Vasta PJ, Kondraske GV: An Approach to Estimating Performance Capacity Envelopes: Knee Extensor System Example. Proceedings of the 19th Annual Engineering in Medicine and Biology Society Conference, pp. 1713-1716, 1997

Musculoskeletal Performance Capacity Envelope Estimation

Final Technical Report

Human Performance Institute
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P.O. Box 19180
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HPI Technical Report TR98-007

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Submitted to:

Center for Disease Control and Prevention
National Institute for Occupational Safety and Health

in partial fulfillment of reporting requirements for

Grant No.: 5 R03 OH03336-01

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List of Abbreviations

CAV	Constant Angular Velocity
ERM	Elemental Resource Model
GSPT	General Systems Performance Theory
PCE	Performance Capacity Envelope

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Significant Findings

The following findings significant findings are reported:

- A mathematical model representing the "shape" of a normalized three-dimensional performance capacity envelope (torque available, joint angle, and speed) for the knee extensor subsystem of humans in general was obtained that requires only specification of five unknowns (i.e., only five measurements are required) to individualize for a specific member of the human population.
- Once actual measurements for a specific subject are utilized to "warp" or scale the general PCE shape model to represent that individual, anthropometric factors (height, weight, limb segment lengths, etc.) add little to the overall fidelity of the model.
- For the knee extensor system studied, five torque availability measurements for a particular individual, combined with a statistical representation of the shape of the PCE for the general population, provide a representation of that individual's PCE with a fidelity that is essentially equivalent to that obtained by making a large number of measurements that sample the PCE surface. Out of many combinations studied, the five measurements include three isometric stength torques (at knee flexion-extension angles of 110, 65, and 10 deg; i.e., two near the extremes and one near the mid-point or peak in the torque vs. angle curve) and two isokinetic torques values (at 150 deg/s and joint angles of 10 and 100 deg; i.e. one value near each extreme of motion).
- A meaningful standard for judging the quality of predictive models intended to substitute for direct measurements of variables is the degree of error observed during repeated direct measurement; i.e. no better performance can be expected from prediction than that which is observed during repeat testing. It is noted that variability in a human's ability to repeat a maximal capacity effort contributes to the process of judging predictive ability of models.
- The multidimensional PCE presented has been found to be succint way to capture and represent major aspects of the the performance capacity of the knee extensor system, and perhaps other musculoskeletal systems.
- The data collected represents one of the most comprehensive data sets known to exist for the knee extensor system.
- There is some evidence to suggest that fatigue during traditional continuous isokinetic protocol may result in an underestimate of available torque (at angles subsequent to initial angles) and that the modified continuous approach used herein may offer more accurate estimates when attempting to establish true values of performance capacities.

Usefulness of Findings

The findings are considered to be useful from several perspectives. These are:

- Characterization of Musculoskeletal Performance: A general "systems approach" has been demonstrated for characterizing all aspects of the performance capacity of a musculoskeletal subsystem. The PCE approach is introduced, based on General Systems Performance Theory (GSPT), which provides a means of unifying the understanding of previous characterization efforts executed at both basic science and clinical levels. It is anticipated that the PCE approach will significantly and positively contribute to debate about what measurements to make and how to make them when attempting to quantifying musculoskeletal systems performance for both clinical and research applications. Furthermore, the experimental methods of the present study can serve as a model for investigations aimed at development of PCEs for other musculoskeletal subsystems.

- Characterization of Performance Capacities of Other Physiologic Systems: Due to its generalizability, it is anticipated that the PCE approach and GSPT on which it is based may be recognized, adopted, and extended to other subsystem types by researchers working at various physiologic levels within the hierarchy of human performance (e.g., cellular, organ, subsystem, and complex task level).

- Support for Cause-Effect Models to Predict Performance In Complex Tasks/Injury Prevention: Findings are useful in the context of the broader and more complex task of relating characteristics of a set of subsystems (e.g., flexors, extensors, etc.) - for a particular individual - that work together to form some more complex system (e.g., a lifting system) to the level of performance that the higher level system can achieve in its task. The ability to do this has been the goal of much research and is considered to be an important basis for injury understanding and prevention. The ability to obtain a reasonable fidelity representation of the PCE for one musculoskeletal subsystem (e.g., the knee extensor) using a General Population Model and only a small number of measurements for a specific individual demonstrates that one of the major component of this complex process (i.e., obtaining an high fidelity quantification of the PCE for a particular individual) can be accomplished in a clinically feasible and practical manner. In actual applications, the desired predictions are likely to require individualized PCEs for more than one musculoskeletal subsystem, which results in a multiplicative benefit of needing only a small subset of measurements for each subsystem.

- Design of New Measurement Tools and Protocols: Results suggest that it may be possible to develop systems for characterization of musculoskeletal PCEs that incorporate much less costly hardware than present isokinetic test systems (for example, only three isometric and two isokinetic torque values are used to obtain a PCE for a specific individual) and much less test administration time than currently used protocols. In addition, there are practical implications associated with the databasing of measurement results. Perhaps only the coefficients of the PCE model need be saved for a particular individual (e.g, five values vs. many thousands of values).

Abstract

The purpose of this study was to develop and evaluate an approach to modeling multidimensional (strength, joint angle, and speed) performance capacity envelopes that more completely characterize specific human musculoskeletal subsystems (e.g., trunk extensor, wrist extensor). This is a logical extension to the typical two-dimensional families of curves produced by isokinetic measures, which provide only limited utility.

Isometric and new modified isokinetic protocols were used to obtain a parametric data set for each of 35 healthy volunteers, using the knee extensor as a representative subsystem for the approach. Using data for 21 subjects (Phase I of data collection), the functional form of a normalized three-dimensional performance capacity envelope representing the general population was determined using statistical analysis of the subject data. A limited subset of each subject's data was then used in combination with the general population model to derive higher-fidelity subject-specific models (i.e., mathematical representations of the the three-dimensional performance capacity envelopes. The estimated knee extensor torque capacity of each model was compared to the measured torque values. The approach provided torque capacity estimates that were comparable to test-retest accuracy. The analysis was repeated using data from an additional 14 subjects (Phase II of data collection). While the general model used to derive subject specific models was derived from the Phase I subjects, prediction accuracy was again generally comparable to test-retest accuracy.

It is concluded that the PCE approach is a convenient and concise way to represent the the performance capacity of the knee extensor system. More specifically, experimental results demonstrate that it is possible to obtain a fidelity for representation of the entire envelope *for a particular individual* that is essentially equivalent to that obtained by making a large number of measurements that sample the PCE surface by using a General Population Model that captures the shape of the envelope and a small set of direct measurements that scales or warps the shape model appropriately.

1.0 Introduction

There have been a number of research efforts aimed at producing biomechanical models of one or more musculoskeletal components motivated by a wide range of purposes. One class of such purposes pertains to the ability to relate characteristics of a set of subsystems (e.g., flexors, extensors, etc.) that work together to form some more complex system (e.g., a lifting system) to the level of performance that the higher level system can achieve in its task. In this report, we conceptual strategies and a practical approach for the musculoskeletal subsystem characterization necessary to support such broader endeavors. To provide a specific context for experimental work, we have chosen the knee extensor subsystem as the system of study. This work is also relevant to ongoing efforts that address quantification of musculoskeletal component performance in general.

The approach presented is directly motivated by relatively new work (Kondraske, 1987; Kondraske 1995; Kondraske et al, 1997) aimed at achieving improved theoretical frameworks for understanding and working with the notion of system performance in general (i.e., General Systems Performance Theory or GSPT) and, more specifically, human performance (i.e., the Elemental Resource Model or the ERM). Here, we directly apply the concepts of GSPT, which in part provides a general approach for characterizing the performance capacity of any system, to the knee extensor system. This results in the introduction of the notion of a performance capacity envelope (PCE) for musculoskeletal systems (e.g., knee flexor and extensor, trunk flexor and extensor, etc.).

Recognizing that clinical applications require data collection in situations where time is precious, we also address the practical question "How much data is necessary to achieve a reasonable fidelity representation of a PCE for a specific individual?". The concept investigated is that a small number of measurements for a particular individual, combined with a statistical representation of the shape of the PCE for the general population, would provide a representation of that individual's PCE with a fidelity that would be essentially equivalent to that obtained by making a large number of measurements that sample the PCE surface.

1.1 Specific Aims

The specific aims of this study were to:

1. Combine the concepts and results of previous studies in physiology, biomechanics performance analysis, and systems engineering as well as experimental performance data to develop a general, population-based musculoskeletal subsystem multi-dimensional performance envelope model.
2. Utilize the functional form resulting from (1); i.e., the mathematics that describes the envelope shape (but not "size"), and a subset of performance measurements for each individual (that provides "sizing" information) in a sample population to derive subject-specific performance envelope models.
3. Utilize the equation coefficients determined in (1) as well as anthropometric and/or demographic information to "warp" the corresponding equations derived (2) and investigate any change in model prediction accuracy. Positive effects will provide impetus for incorporating the resulting scheme in the final methodology.
4. Test the validity of the methodology through statistical examination of prediction errors for the specific subject models to obtain a scientifically sound conclusion regarding the adequacy of the proposed methodology with respect to the specific hypothesis put forth.

5. Investigate the content validity of the standard isokinetic test protocol for the knee extensor using previously collected data via comparison to data obtained with the modified isokinetic protocol (intended to reduce fatigue effects) used in this study.

1.2 Background

There is substantial experimental data across multiple independent studies involving different subjects that indicate the existence of some generalizable functional relationships between selected performance variables within the human musculoskeletal architecture. First, the length-tension relationship of isometric muscle contraction (M.G. Hoy, F.E. Zajac, and M.E. Grodon, 1990) and second the relationship between torque production and joint rotational velocity (Wickiewicz, Roy, Powell, Perrine, and Edgerton, 1984). From an empirical perspective, the results of these and other studies (Afzali, Kuwabara, Zachazewski, Browne, and Robinson, 1992; Perrine and Edgerton, 1978) provide reason to believe that there is an inherent physiologic consistency across humans in the relationship of certain performance variables in two-dimensions. Based on conditional similarities and differences across such studies, this consistency appears to transcend multidimensional performance space, thus providing impetus and further rationale (beyond that independently provided by GSPT) for this study. Additionally, from a clinical perspective, we note that muscle and exercise physiology researchers have recognized the value of investigating and understanding interactions of performance variables that represent unique and different aspects of performance.

While studies are present in the literature that utilize single performance variables or performance resources from across functional units or hierarchical levels, the concept of a "performance envelope," identified in GSPT (Kondraske, 1995) as a *sine qua non* of understanding system-task interfaces, appears to be absent in related bodies of literature. Nonetheless, while quantitative models that capture multidimensional interactions for a specific functional unit have not yet been presented, three of the more pertinent generalizable findings reported <u>across</u> (but not within) <u>related studies</u> are: (1) torque values obtained for a given angular position are greatest when measured at low velocities (isometrically or near zero degrees per second), (2) torque production capacity decreases as rotational velocity increases, and (3) the torque-joint angle functional relationship is approximately maintained with increasing rotational velocity.

Musculoskeletal relationships such as these have important implications from a muscle physiology perspective, where links between observations using current measurement protocols (i.e., dynamometry) and the underlying morphology and mechanisms have received considerable attention from researchers (Jones, McCartney, and McComas, 1986; Basmajian and Deluca, 1985). However, far less effort has been put forth regarding such research linked to occupational health issues. In contrast to physiologic research, where observations range from the musculoskeletal unit down to underlying structures and mechanisms, occupational health studies more often address observations that range from the musculoskeletal unit (or units) up to the higher level task.

1.3 Approach Overview and Modifications to Original Plan

The specific approach involves defining a model that captures the essence of the shape of the PCE of a given subsystem for humans in general (i.e., the General Population Model) and then using a small set of measurements from a specific individual to "warp" the General Population Model into a Specific Subject Model. The Specific Subject Model may then be exercised as needed to obtain the desired information (e.g., torque available for a specific joint angle and movement speed) for that individual.

It was originally planned to include 40 subjects (20 males and 20 females) in the study. Thirty subjects were to be used to derive a model representing the shape of the performance capacity envelope (the so-called "General Population Model). It was further planned to use data from 10 additional subjects to test the prediction capability; i.e., (1) a small subset of measured data from these subjects was to be used with the General Population Model to obtain "Subject Specific" Models for each individual's performance capacity envelope and (2) the Subject Specific Models would then be used to make torque predictions at speeds and angles where measurement data existed for these 10 subjects, and (3) the measured values would then be compared to the predicted values. A summary of the original approach is provided in Figure 1.

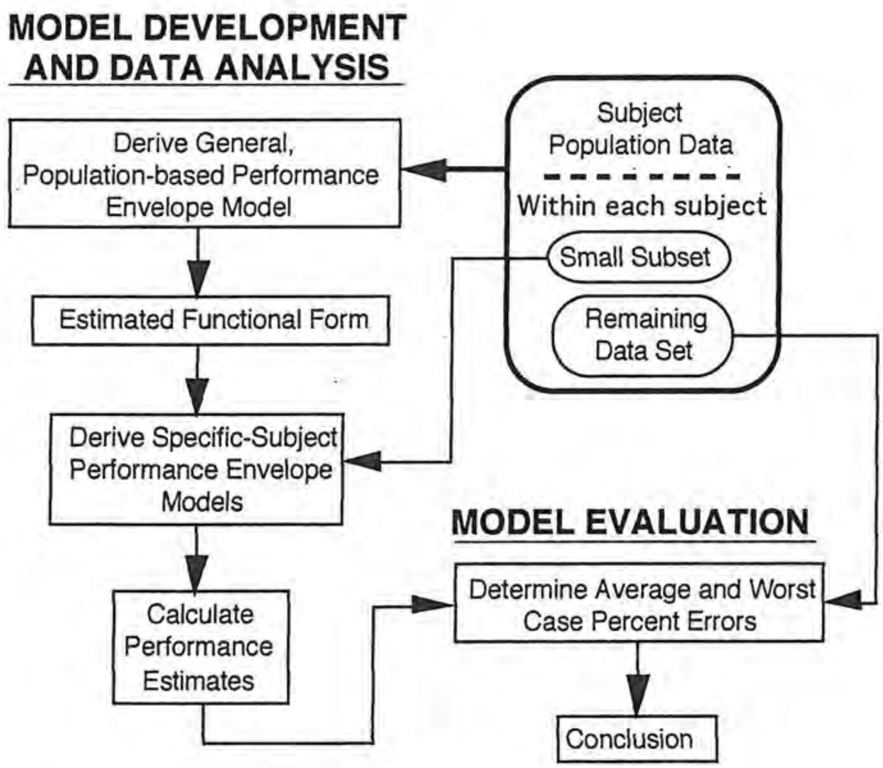

Figure 1. Block diagram of major components of the experimental study.

The essence of the orignal strategy has remained intact. However, modifications were made as follows:

- Data was collected in two phases: Phase I (n = 21) and Phase II (n = 14). The total number of subjects test is 35 (vs. 40).
- Data from Phase I was used to derive the General Population Model and to assess the ability of the all 21 Subject Specific Models to predict the performance capacity envelopes for the respective subject.
- Data from Phase II was used with the Phase I General Population Model to derive 14 new Subject Specific Models and again prediction accuracy was assessed.

Modifications associated with overall sample size were necessary due to problems recruiting subjects according to desired race and gender distributions, coupled with the timing of co-investigator Vasta's graduate work.

The change whereby prediction accuracy was investigated for each subject's Subject Specific Model was made to take advantage of insights that emerged early in the project regarding an appropriate "gold standard for comparison". Specifically, it was realized that predictions (e.g., predicted torque given a speed and an angle) could not be expected to be closer to a "measured value" than another measurement. Thus, the difference between predicted and measured (i.e., "error" was compared to the difference between actual "test" and "retest" measurements.

2.0 Experimental Methods

2.1 Subjects

In Phase I, twenty-one university students and faculty (11 males and 10 females) of various ethnic backgrounds participated in the study [8]. The mean (standard deviation; range) age, body weight and stature of the males were 27.6 (±4.3; 22-38) years, 80.6 (±9.0; 71.6-100) kg and 179.0 (±7.3; 173-197) cm, respectively. The mean (standard deviation; range) age, body weight and stature of the females were 27.6 (±7.0; 22-45) years, 57.4 (±5.9; 50.8-71.2) kg and 163.5 (±3.5; 157-169.5) cm, respectively.

For Phase II, fourteen university students and non-students (4 males and 10 females) of various ethnic backgrounds. The mean (standard deviation; range) age, body weight, and stature of the males were 27.5 (4.65; 23-34) years, 70.9 (±6.7; 62-77) kg, and 174.1 (±6.25; 168-180) cm, respectively. The mean (standard deviation; range) age, body weight, and stature of the females were 29.6 (±6.2; 23-41) years, 64.4 (±7.7; 57-79) kg, and 162.6 (±4.8; 157-171) cm, respectively.

For the combined Phase I and II subject group, the mean (standard deviation; range) age, body weight, and stature of the males were 27.6 (±4.2; 22-38) years, 78.0 (±9.3; 62-100) kg, and 177.6 (±7.1; 168-197) cm, respectively. The mean (standard deviation; range) age, body weight, and stature of the females were 28.6 (±6.5; 22-45) years, 60.9 (±7.6; 51-79) kg, and 163.1 (±4.1; 157-171) cm, respectively. The distriubtion of subjects by gender and race is summarized in Table 1.

Table 1. Distribution of subjects by gender and race.

Category	Phase I Percentage (n)	Phase II Percentage (n)	Cummulative Percentage (n)
Male	52.4 (11)	28.6 (4)	42.9 (15)
Female	47.6 (10)	71.4 (10)	57.1 (20)
Total	100.0 (21)	100.0 (14)	100.0 (35)
White	80.0 (17)	50.0 (7)	68.6 (24)
African American	0.0 (0)	21.4 (3)	9.7 (3)
Hispanic	9.5 (2)	14.3 (2)	11.4 (4)
Asian	4.8 (1)	0.0 (0)	2.9 (1)
Other	4.8 (1)	14.3 (2)	9.7 (3)
Total	100.0 (21)	100.0 (14)	100.0 (35)

For Phases I and II, all subjects were active, in good health and reasonable fitness at the time of testing and possessed no special athletic ability. All data collection was performed in a single session.

2.2 Equipment and Data Collection Procedures

Anthropometric measures were taken and each subject performed warm-up and stretching exercises prior to testing. All performance capacity measurements were performed on a Kin-Com II dynamometer. Subjects were seated at approximately 90 degrees of hip flexion and restraint straps were placed at the thigh and waist. Gravity-correction (Winter, Wells, and Orr, 1981) was implemented to reduce errors in torque measurement.

Given the desire to obtain measures of maximum available torque, the traditional approach to measuring maximal torque as a function of angle, while moving at a constant angular velocity (CAV) was not considered to provide adequate isolation of strength from endurance (assuming other factors, like motivation, etc., are non-limiting). The approach used here to counteract this effect was to measure strength in small intervals corresponding to selected test angles across the range of motion. This effect and a similar protocol has been reported in the literature (Wickiewicz, Roy, Powell, Perrine, and Edgerton, 1984; Perrine and Edgerton, 1978). Torque availability samples that map out the surface of the desired PCE were obtained by examining torque at five different angles for each of five different speeds (including isometric). Details of this protocol are summarized in Table 2.

The isometric protocol was administered first followed by the CAV protocol in order of increasing velocity to allow the subject to gradually become familiar with the increasing knee extension speeds and to maximize the reliability of the measures (Wilhite, Cohen, and S.C. Wilhite, 1992). The order of the test angles were randomized across subjects (but were consistent across velocities within subjects). Practice trials were provided before both isometric and CAV testing. The subjects were verbally instructed on the protocol prior to each test but not encouraged during exercise. At each of the five angular positions for the isometric tests, the subjects were required to exert maximal effort for three seconds. Two minute rest periods between each position were included to minimize fatigue effects. Rest periods of 45 seconds were provided between CAV intervals within the same velocity and a two-minute rest was provided between each velocity.

For each subject, the entire protocol was administered once and then repeated using the same randomization within the same session.

Table 2. Details of measurement protocol used to map the knee extensor performance capacity envelope.

Mode	Velocity (deg/sec)	Target Angle† (deg)	Start Angle† (deg)	Stop Angle† (deg)	Post-Trial Rest (min)
Isometric	0	80 (practice)	80	80	2
Isometric	0	110	110	110	2
Isometric	0	80	80	80	2
Isometric	0	65	65	65	2
Isometric	0	50	50	50	2
Isometric	0	10	10	10	2
CAV	50	Full (practice)	115	0	.75/2
CAV	50	Full	115	0	.75
CAV	50	105	115	95	.75
CAV	50	80	90	70	.75
CAV	50	65	75	55	.75
CAV	50	50	60	40	.75
CAV	50	10	20	0	.75
CAV	100	Full (practice)	115	0	.75/2
CAV	100	Full	115	0	.75
CAV	100	100	115	90	.75
CAV	100	80	95	70	.75
CAV	100	65	80	55	.75
CAV	100	50	65	40	.75
CAV	100	10	25	0	.75
CAV	150	Full (practice)	115	0	.75/2
CAV	150	Full	115	0	.75
CAV	150	95	115	85	.75
CAV	150	80	100	70	.75
CAV	150	65	85	55	.75
CAV	150	50	70	40	.75
CAV	150	10	30	0	.75
CAV	200	Full (practice)	115	0	.75/2
CAV	200	Full	115	0	.75
CAV	200	90	115	80	.75
CAV	200	80	105	70	.75
CAV	200	65	90	55	.75
CAV	200	50	75	40	.75
CAV	200	10	35	0	.75

† zero degrees = full extension

* rest period between intervals within trials / rest period between trials

2.3 Data Analysis

For each isometric case, data samples making up the plateau portion (i.e., between the initial increase of torque from rest and the initial decrease at relaxation) of the curve were averaged to determine a peak torque value estimate for the respective joint angle. For each CAV interval, torque samples over a range of ±5 degrees from the target angle were averaged in an effort to reduce the effects of noise. Each subject's data was normalized to his or her isometric torque at 80 degrees of knee flexion (representing peak torque for most subjects), providing a common scale across subjects along the torque axis. The normalized data was then screened for quality including motivation effects by examining outlying values using Tukey's "rule of thumb" [11]. For each subject of the final sample population, the 50 torque values were reduced to 25 representing the final working data set by examining the area under each torque/angle curve. Five data points for each subject were extracted to form the data subset used to derive the specific-subject model and the remaining twenty data points were used to produce the general population-based model.

The General Population Model was derived through statistical multiple regression analysis using the entire Phase I data set. Various functional forms (as indicated by scatter plots of the data) for the isometric and CAV relationships were combined and the resulting three-dimensional function forms were examined as possible candidates for the final model. The function chosen was determined based on the reduction in mean square error (i.e., R-square) and Mallows C_p statistic, as compared to other functions (i.e., All-Possible Regression procedure described in Neter, Wasserman and Kutner, 1990), and the number of data points required to derive the coefficients of the representative equation. Thus, the "most reasonable" function for the intended purpose was chosen.

Specific Subject Models were built for each of the 21 Phase I subjects by deriving coefficients for the General Population Model using a small subset of measurements (five torque points) for each subject. The five measurements used include three isometric stength torques (at knee flexion-extension angles of 110, 65, and 10 deg; i.e., two near the extremes and one near the mid-point or peak in the torque vs. angle curve) and two isokinetic torques values (at 150 deg/s and joint angles of 10 and 100 deg; i.e. one value near each extreme of motion). Incorporation of this data results in five equations that are solved simulataneously to obtain coefficients b_0 through b_4 for a given subject.

For Phase II, the original General Population Model that was derived using Phase I subjects was used along with Phase II data to generate Specific Subject Models for each of the 14 Phase II subjects.

For Phase I and Phase II (separately), average and worst-case errors (estimates vs. measured) were then calculated across all data points of the large data subset (n=20) for each of the Specific Subject Models. These errors were compared to average and worst-case errors between trials, using test-retest accuracy (from actual measurements) as a "gold standard" for comparison.

3.0 Results

3.1 Phase I Results

The Tukey "rule of thumb" procedure indicated four subjects for removal from the sample population. For the remaining 18 subjects, scatterplots of the normalized torque data were created to aid in selecting the following independent variable candidates for the model:

$$A, A^2, A^3, V, V^2, e^{-(V/75)}, \text{and } AV$$

where A = knee flexion angle and V = knee joint angular velocity.

SAS statistical analysis software was utilized in determining the "best" set of independent variables for inclusion. Additionally, variance inflation factors were derived and examined to address concerns regarding multicolinearity. Standard statistical assumptions including constant variance of errors and model adeuqacy were also addressed through examining residual plots and performing a lack of fit test, respectively. No indication of departure from assumptions were found.

The final general, population-based model was found to be of the form:

$$\text{Torque} = b_0 + b_1\text{Angle}^2 + b_2\text{Angle}^3 + b_3e^{(-\text{Velocity}/75)} + b_4(\text{Angle x Velocity})$$

This model represents the shape of the knee extensor PCE for the general population. A 3-dimensional plot of the General Population Model is shown below in Figure 2.

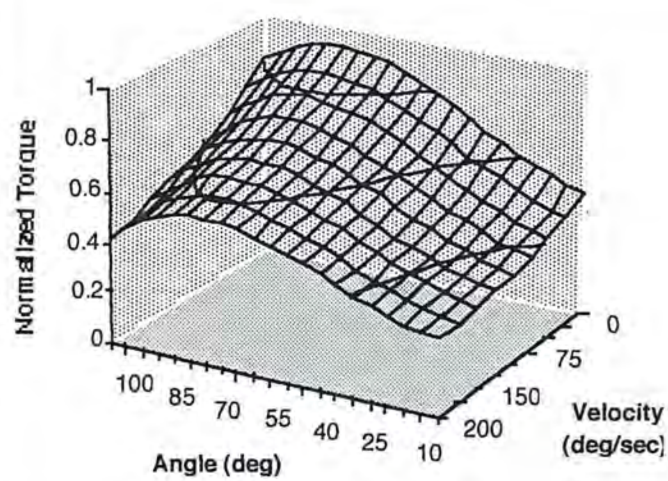

Figure 2. Knee extension performance capacity envelope for the "general population".

The Subject Specific Models were derived using only five measurements that allowed specification of the five coefficients in the General Population Model (b_0 - b_4) for each subject. These values are tabulated in Table 3 and can be used to determine torque availability for any angle and velocity combination for a given subject (refer to Section 3.3).

Table 3. Coefficients used to form Specific Subject Models for each of the 21 subjects that participated in Phase I data collection.

Subject ID	B_0 (torque intercept, N-m)	B_1 (deg^2)	B_2 (deg^3)	B_3 (N-m)	B_4 (deg^2/sec)
43	97.1119817	0.07554535	-0.0005734	24.75728270	-0.0085362
372	78.9399534	0.05914629	-0.0005015	14.87581810	-0.0052426
494	63.9108481	0.07550365	-0.0006125	-2.25400050	-0.0069955
701	37.6422521	0.00495712	-2.972E-05	17.33339920	-0.0004696
609	66.7260409	0.07542139	-0.0005969	-17.19763900	-0.0096027
891	37.6069876	0.01761771	-0.0001266	13.80264210	-0.0020239
384	63.1125073	0.04833719	-0.0003861	13.62243260	-0.0049683
606	39.9967879	0.04343214	-0.0003712	5.69934207	-0.0040644
893	63.6535207	0.04434457	-0.0003287	0.12111395	-0.0068844
411	51.2035759	0.03220124	-0.0002611	8.89840920	-0.0042371
339	57.8622054	0.04170339	-0.0003327	0.84060829	-0.0035791
80	52.5408918	0.07019669	-0.0006011	17.98386340	-0.0075638
822	57.9544215	0.04039958	-0.0003294	-0.54795930	-0.0051782
429	55.8058291	0.03083603	-0.0002330	1.12603139	-0.0044352
632	79.5613024	0.05608685	-0.0004283	-41.87437600	-0.0076335
863	47.3610472	0.02143235	-0.0001611	10.87452270	-0.0038009
965	40.2182449	0.02177577	-0.0001841	11.88322050	-0.0019113
590	64.0842927	0.01974803	-0.0001738	-8.58527900	-0.0004156
492	55.9977420	0.01250692	-0.0001016	2.95313186	-9.769E-05
340	45.8886374	0.00721299	-0.0000487	21.37320980	-0.0002555
162	32.1780536	0.02399249	-0.0002108	13.93345700	-0.0027015

The Subject Specific Models were derived and average and worst-case estimation errors were calculated for each subject. A similar procedure was followed for determining average and worst-case errors between trials. Results for the Phase I group are shown in Table 4.

Table 4. Evaluation of performance capacity envelope estimation for Phase I subject group (n = 21) using actual repeated measurement as a basis of comparison.

	Model Estimates vs. Measurements	"Test" Measurement vs. "Retest" Measurement
Average absolute prediction error (%)	12.2	10.6
Worst-case % error	54.5	61.8

3.2 Phase II Results

Coefficients that form the Specific Subject Models for Phase II subjects are tabulated in Table 5.

Table 5. Coefficients used to form Specific Subject Models for each of the 14 subjects that participated in Phase II data collection.

Subject ID	B0 (torque intercept, N-m)	B1 (deg^2)	B2 (deg^3)	B3 (N-m)	B4 (deg^2/sec)
740	36.5413023	0.01767885	-0.0001596	6.50782558	-0.0015054
53	47.1460282	0.02180658	-0.0001847	-0.750536	-0.002217
49	54.883361	0.054104	-0.0004276	2.89106813	-0.0070902
37	60.1670691	0.05425710	-0.0004766	7.00844956	-0.0060199
91	47.1920197	0.01707439	-0.0001239	9.75109728	-0.0026461
362	46.5840601	0.03203277	-0.0002607	1.11170026	-0.0021963
199	41.6788904	0.02331079	-0.0002063	1.37528702	-0.0018657
794	34.5609881	0.01934364	-0.0001634	25.3848054	-0.0011067
759	40.8619308	0.01652637	-0.0001324	-2.9351926	-0.0009718
57	56.2255563	0.03359214	-0.0002708	-11.77935	-0.0041707
580	28.5007285	0.02192617	-0.0001795	10.1657833	-0.002443
710	39.4108341	0.02978851	-0.0002352	12.5927831	-0.0040259
575	40.6704338	0.018938	-0.0001507	16.1029144	-0.0028445
495	36.0381773	0.0160942	-0.0001134	1.49560339	-0.0020832

Evaluation of the PCE prediction accuracy for Phase II subjects is summarized in Table 6.

Table 6. Evaluation of performance capacity envelope estimation for Phase II subject group (n=14) using actual repeated measurement as a basis of comparison.

	Model Estimates vs. Measurements	"Test" Measurement vs. "Retest" Measurement
Average absolute prediction error (%)	12.3	15.1
Worst-case % error	76.5	113.6

3.3 Individualized Performance Capacity Envelope Examples

Three representative PCEs, generated from selected Specific Subject Models in Tables 3 and 5 above, are presented below.

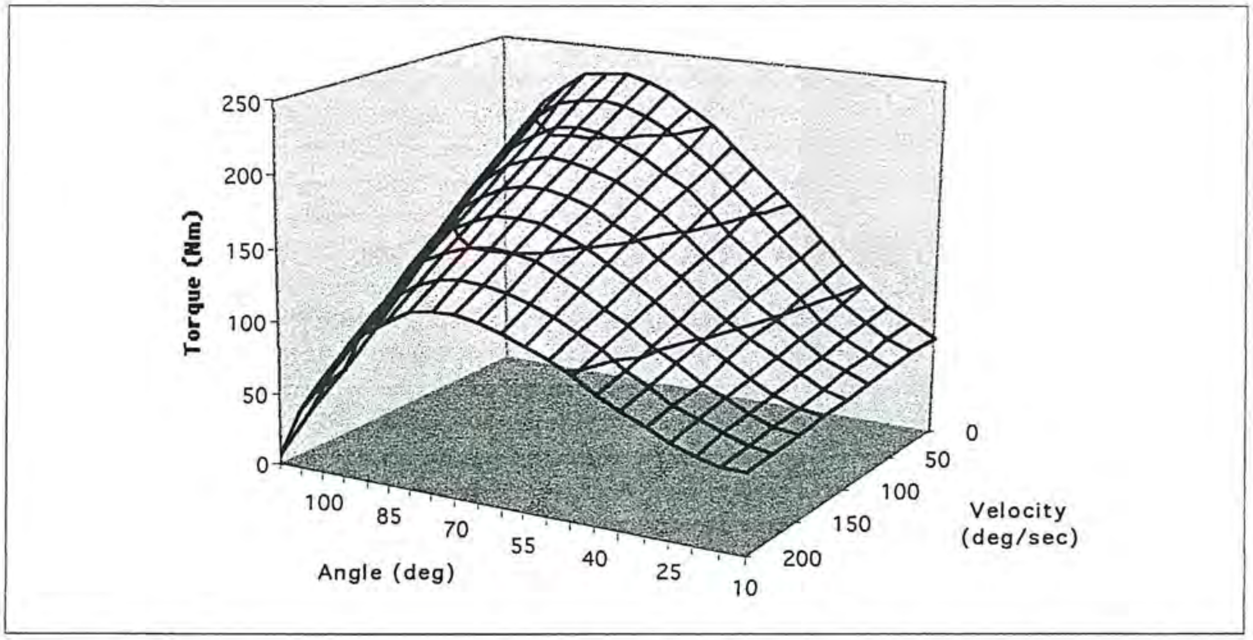

Figure 3. Performance Capacity Envelope surface plot for Subject 494 (27 year-old white male, Phase I subject).

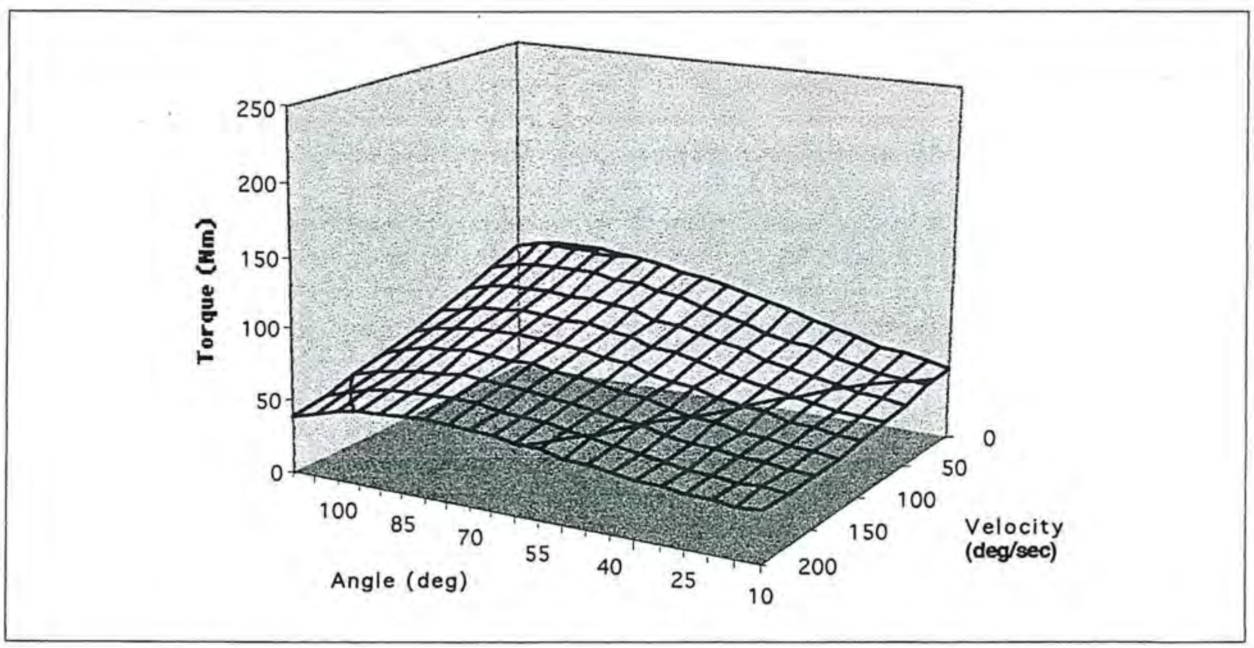

Figure 4. Performance Capacity Envelope surface plot for Subject 891 (22 year-old Hispanic Female, Phase I subject).

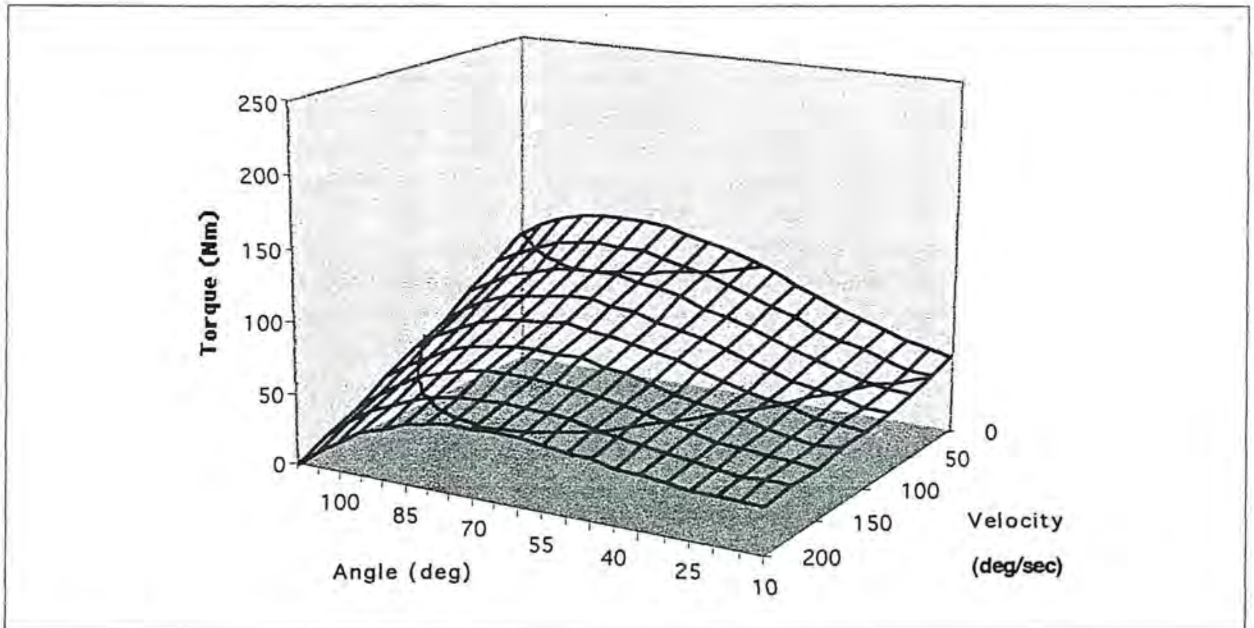

Figure 5. Performance Capacity Envelope surface plot for Subject 710 (25 year-old African-American Female, Phase II subject).

4.0 Work in Progress

The data set is rich and provides the opportunity for many other investigations. Work is in progress to further explore the tradeoffs between measurement effort and fidelity of the PCE representation. It may be possible to provide researchers and clinicians with models that require fewer measurements to populate, with a known loss of accuracy. Such tradeoffs may be warranted.

Data analysis as reported here is performed for Phase I data sets separately. Recent investigation indicates that there would be no change to the General Population Model (where only the form of the mathematical function is important, not the coefficients) if it were derived using Phase II data. For a pending publication (see Section 9.0), we are pooling Phase I and Phase II data and examining/reporting prediction accuracy for all 35 subjects as a single group.

While not an original objective, we are also investigating the use of Specific Subject Models obtained in this study as a basis for establishing normal limits for the knee extensor PCE (i.e., a range of torque availability for several selected angle and speed combinations) that could be useful clinically.

5.0 Discussion

A mathematical model representing the "shape" of a normalized three-dimensional performance capacity envelope (torque available, joint angle, and speed) for the knee extensor subsystem of humans in general was obtained that requires only specification of five unknowns to individualize (i.e., only five measurements are required) for a specific member of the human population. For the knee extensor system studied, five torque availability measurements for a particular individual, combined with a statistical representation of the shape of the PCE for the general population, provide a representation of that individual's PCE with a fidelity that is essentially equivalent to that obtained by making a large number of measurements that sample the PCE surface (Tables 4 and 6).

From an absolute measurement perspective, the level of agreement between model predictions and measurements is considered to be quite good. Simply put, the models reliably produce valid estimates of torque availability. The worst-case extremes noted must be kept in perspective. Note that they too are worse for actual test-retest measurement differences than for model-measurement differences. For each subject, there are 25 torque samples corresponding to different angle and velocity combinations. Twenty of these are used to evaluate prediction accuracy. The five sample used to form the Specific Subject Model were excluded; their inclusion would result in improved accuracy which might be considered an unfair biasing by some. Thus, the combined Phase I and Phase II evaluations include 20 x 35 = 700 comparisons. Worst-case can be established by any one of these. Since both test-retest and model-measurement worst-case errors are large, such extremes are most likely due to measurement error and not some aspect of the PCE modeling approach.

Out of many combinations studied, the five measurements include three isometric stength torques (at knee flexion-extension angles of 110, 65, and 10 deg; i.e., two near the extremes and one near the mid-point or peak in the torque vs. angle curve) and two isokinetic torques values (at 150 deg/s and joint angles of 10 and 100 deg; i.e. one value near each extreme of motion). It was found that once actual measurements for a specific subject are utilized to "warp" or scale the general PCE shape model to represent that individual, anthropometric factors (height, weight, limb segment lengths, etc.) added little to the overall fidelity of the model.

All aspects of the PCEs derived from the Specific Subject Models agree well with features expected based on compilation of previous two dimensional studies. To further evaluate the approach quantitatively, we attempted to find data in the literature that could be used to derive Specific Subject PCE Models for subjects in other studies. Interestingly, no reports could be found that contained sufficient data *for a the same subject* to solve for the five model coefficients. We believe that the present study represents one of the most comprehensive efforts to characterize knee extensor performance.

A meaningful standard is introduced for judging the quality of predictive models that are intended to substitute for direct measurements of variables; i.e. the degree of error observed during repeated direct measurement; i.e. no better performance can be expected from prediction than that which is observed during repeat testing. It is noted that variability in a human's ability to repeat a maximal capacity effort contributes to the process of judging predictive ability of models.

Findings are useful in the context of the broader and more complex task of relating characteristics of a set of subsystems (e.g., flexors, extensors, etc.) - for a particular individual - that work together to form some more complex system (e.g., a lifting system) to the level of performance that the higher level system can achieve in its task. The ability to do this has been the goal of much research and is considered to be an important basis for injury understanding and prevention. The ability to obtain a reasonable fidelity representation of the PCE for one musculoskeletal subsystem (e.g., the knee extensor) using a General Population Model and only a small number of measurements for a specific individual demonstrates that one of the major component of this complex process (i.e., obtaining an high fidelity quantification of the PCE for a particular individual) can be accomplished in a clinically feasible and practical manner. In actual applications, the desired predictions are likely to require individualized PCEs for more than one musculoskeletal subsystem, which results in a multiplicative benefit of needing only a small subset of measurements for each subsystem.

The current study is viewed as a natural extension of our GSPT and ERM research. It specifically contributes to issues of practical concern. If one desires to estimate performance in a higher level task for a specific individual, for example (Kondraske et al, 1997), it is possible to estimate the performance capacity envelope for one of the involved subsystems (and, by inference, others) using only a small subset of data (relative to that which would otherwise be required to obtain a high fidelity representation using only direct measurement). This is aimed at the objective of providing a rapid and efficient means for use clinically and in other settings where such efforts might be undertaken. The value of this study is not in the specific numerical data obtained, per se, but rather in the light shed on the general purpose approach demonstrated.

GSPT and the ERM call for cause-and-effect as opposed to a statistical (i.e., regression) approach in estimating high level task performance from performance capacities of lower level subsystems. Fundamental limitations of the latter have been presented elsewhere (Kondraske and Beehler, 1994). With regard to the former, direct analysis and inferential methods (Vasta and Kondraske, 1994) have been proposed. This current work contributes to the direct analysis approach.
Statistical approaches, require a separate experimental data gathering and model buliding effort to arrive at a model for each higher level task. In contrast, individual, Subject Specific Models, to be built upon the general model described here, will require data only for the specific subject of interest and only for the lower level performance capacities (as well as structural parameters such as link lengths required in the analytic mappings). Thus, while a separate analytic set-up (or model) is required for each task, this is not data dependent in the same fashion as regression models. Also, while population data may be useful to estimate some performance capacities of a single subject (in lieu of direct measurement), the present thesis does not go so far as to resort *only* to population data. Rather, the notion is introduced of making a small set of measures on the specific individual and using information about the shape of the performance capacity envelope obtained from population studies (e.g., the general model presented here) as a means to improve fidelity (over simply using a population database) that would otherwise result *for that individual.* This is seen as a compromise between using simply population statistics as estimates (lower fidelity, but rapid) and direct measurement of all points required to define the performance envelope (highest fidelity, but time intensive). Additionally, this approach will provide a means toward reducing performance measures into a composite index, something that has been desired but lacking in clinical decision making.

Results suggest that it may be possible to develop systems for characterization of musculoskeletal PCEs that incorporate much less costly hardware than present isokinetic test systems (for example, only three isometric and two isokinetic torque values are used to obtain a PCE for a specific individual) and much less test administration time than currently used protocols. In addition, there are practical implications associated with the databasing of measurement results. Perhaps only the coefficients of the PCE model need be saved for a particular individual (e.g, five values vs. many thousands of values).

6.0 Conclusions

It is concluded that the PCE approach is a convenient and concise way to represent the the performance capacity of the knee extensor system. More specifically, experimental results demonstrate that it is possible to obtain a fidelity for representation of the entire envelope for a particular individual that is essentially equivalent to that obtained by making a large number of measurements that sample the PCE surface by using a General Population Model that captures the shape of the envelope and a small set of direct measurements that scales or warps the shape model appropriately.

A general "systems approach" has been demonstrated for characterizing all aspects of the performance capacity of a musculoskeletal subsystem. The PCE approach is introduced, based on General Systems Performance Theory (GSPT), which provides a means of unifying the understanding of previous characterization efforts executed at both basic science and clinical levels.

It is anticipated that the PCE approach will significantly and positively contribute to debate about what measurements to make and how to make them when attempting to quantifying musculoskeletal systems performance for both clinical and research applications. Furthermore, the experimental methods of the present study can serve as a model for investigations aimed at development of PCEs for other musculoskeletal subsystems.

This study addresses an important step in the process of using cause-and-effect methods to estimate the level of performance that an individual can obtain in a higher level task (e.g., walking or stair climbing) using data representing performance capacities of lower level subsystems such as knee extensors, flexors, etc. The performance capacity associated with any one of these lower level subsystems is represented by a PCE of the form presented here. This capability opens the door to new, more efficient protocols for clinical measurements without sacraficing fidelity. Thus, this work to raises awareness regarding the definition of multi-dimensional performance capacity envelopes, their importance, and methods to obtain data to define them. Due to its generalizability, it is anticipated that the PCE approach and GSPT on which it is based may be recognized, adopted, and extended to other subsystem types by researchers working at various physiologic levels within the hierarchy of human performance (e.g., cellular, organ, subsystem, and complex task level).

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9.0 List of Present and Planned Publications

Vasta, P. (1995). *An approach to musculoskeletal performance capacity envelope estimation.* Doctoral Dissertation, Arlington, TX: University of Texas at Arlington.

Vasta, P. J., & Kondraske, G. V. (1997). An approach to estimating performance capacity envelopes: knee extensor system example. *Proceedings, 19th Annual Engineering in Medicine and Biology Society Conference*, (pp. 1713-1716).

Vasta, P. J., & Kondraske, G. V. (in final preparation). Performance capacity envelope estimation for the knee extensor system, *J. Biomechanics.*

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