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13. ABSTRACT (Maximum 200 Words)

The goals of this project are: 1) to study the temporal relationship between activity level and health status in polio survivors and to compare the results with those obtained from an age-matched control population and 2) to look at the effect of localized muscle weakness and the associated compensation response on performance of a walking task. Simulation modeling techniques will be used to identify factors critical to task performance, which will provide valuable information for optimizing rehabilitation interventions for polio survivors and other populations with lower extremity muscle weakness. To date, a total of 43 polio survivors and 63 controls have been enrolled and tested for Study #1. Preliminary data analysis has begun. An improved baseline has been developed for the simulation model in Study #2. Sensitivity analysis of the model has been completed. Initial IDA assessment of model performance has been performed, and perturbation analysis and interpretation are underway.

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INTRODUCTION

Controversy exists regarding the relationship between strength, functional performance, and health status in the post-polio population, and the role of activity level in this relationship. Polio survivors tend to have a higher incidence of muscle and joint pain and higher levels of fatigue after normal daily activity compared to the general population. One possible explanation is that, because of their residual muscle weakness, polio survivors perform their activities at a higher activity intensity level than their peers, which may, in turn, make them more susceptible to musculoskeletal problems. However, there have not been any systematic studies performed to confirm this theory. Therefore, one of the goals of this project is to study the temporal relationship between activity level and health status in polio survivors and to compare the results with those obtained from an age-matched control population. A need also exists for improved neuromuscular, musculoskeletal, and link segment dynamic models of common daily activities that can be used to predict the compensatory strategies that will be employed when muscle weakness is present. Therefore, another goal of this research is to look at the effect of localized muscle weakness and the associated compensation response on performance of a walking task. Simulation modeling techniques will be used to identify factors critical to task performance, which will provide valuable information for optimizing rehabilitation interventions for polio survivors and other populations with lower extremity muscle weakness.

BODY

Study #1: An Analysis of Health Status and Activity Level in Polio Survivors Over Time

Although the funding for this study was approved in Sept. 2001, negotiations between the administration for the Albert Einstein Healthcare Network and the contracting office for the Department of the Army regarding language included in the grant agreement resulted in a delay in the signing of the final contract to be held up until mid-Sept. 2002. At that time, the inclusion and exclusion criteria were operationalized (Appendix I) and the data collection forms were developed (see Appendix II). We have now just completed our first year of testing.

As of Sept. 10, 2003, a total of 106 subjects had completed at least one of the four required visits. Visit information is summarized in Table 1 and demographic information is listed in Table 2. Of the 43 polio survivors enrolled in the study so far, all but nine reported symptoms of post-polio syndrome.

Table 1. Number of Subjects Who Completed Each Visit as of 9/10/03

Group	Visit 1	Visit 2	Visit 3	Visit 4
Post-polio	43	39	28	4
Control	63	26	12	1

Table 2. Descriptive Statistics

Variable	Post-Polio	Control
# enrolled	43	63
Gender	M-23, F-20	M-22, F-41
Age Range (yr)	50-81	53-89
Age (Mean(SD))	64.54 (8.1)	72.40 (7.9)
PACE score	147.59 (104.1)	162.11 (80.4)
Steps/day	3320.63 (1411.3)	4793.41 (1667.2)

Preliminary data analysis has begun. Analysis of the step monitor data revealed that polio survivors were inactive about 80% of the time, compared to 76% for the controls. For the polio survivors, the greatest proportion of active time was spent at the "low" level, which is defined as less than 15 steps per min and is associated with intermittent activity. Controls, on the other hand, spent the greatest amount of time at the "high" level, which is defined as greater than 30 steps per minute. Controls also had a higher activity frequency level, as measured by both the step monitor in terms of average steps per day and the PACE score, than polio survivors. An estimate of activity intensity was calculated by dividing normal walking speed by maximum walking speed. While polio survivors reported higher mean activity intensity levels on average, there was no significant difference in activity intensity between groups (Mann-Whitney U test statistic = 1210.00, p = 0.127).

The preliminary analysis of the fatigue severity data revealed a significant difference in baseline total fatigue between groups (Mann-Whitney U test statistic = 1007, p = 0.008). The mean fatigue score for polio survivors was significantly higher than that for the controls (34.95 vs. 27.52). One of our a priori hypotheses was that subjects with high activity frequency levels and high activity intensity levels would report greater fatigue than subjects with high activity frequency levels and low activity intensity levels. The reasoning was that subjects who are very active and also work at a level closer to their maximum capacity will be more likely to experience problems related to overuse and report higher levels of fatigue. A preliminary analysis was performed to test this hypothesis, where subjects were ranked with regard to activity intensity and then subjects who were below the median level were designated as having "low" activity intensity scores and subjects above the median were designated as having "high" activity intensity scores. A similar procedure was followed for activity frequency, where the PASE score was used as the outcome measure. There were 26 subjects who fell into the high frequency, high intensity group and 18 subjects who fell into the high frequency, low intensity group. A non-parametric t-test was used to compare the baseline fatigue severity scores between groups. The results did not provide support for our hypothesis. There was no significant difference in fatigue severity at baseline (p = 0.839) between these two groups. Future analysis will look at the daily fatigue ratings obtained from subjects during the week that they were wearing the step monitors. These fatigue ratings are recorded at the end of each day and may have a closer association to daily activity levels than the baseline measure.

Future data analysis will focus on pain severity and changes over time in the pain, fatigue and activity measures. New subjects are continuing to be recruited and we anticipate no problems in meeting the original study goals.

Study #2 Development of a Walking Model for Simulating the Effect of Localized Muscle Weakness

Administrative

1. One of the study Research Assistants (RAs), Thomas Coulter, was unable to fulfill his required commitment to the study for approximately 9 months. Mr. Coulter is a reservist in the National Guard and was activated in December 2002 to support Operation Enduring Freedom. His position was vacant for approximately 9 months. We were unable to identify a suitable replacement during this time. The other study RA, Mausam Patel, was able to contribute additional time to replace half of Mr. Coulter's hours. The remainder of his hours were not covered. Mr. Coulter has since returned from his mission and restarted in his original position as of September 29, 2003.

2. The computers required to develop, run, and test the simulation model were purchased as budgeted. Due to changes in RA operational structure, two computers were obtained. Reduction in computer costs allowed us to obtain the required resources for within the budgeted amount. Originally, it had been desired to have one full time RA. We were unable to find a single RA capable of that time commitment, but were able to find two half-time RAs instead. Since their hours were often coincident, 2 computers were necessary to allow both to work simultaneously. The computers were purchased in project year 2 rather than initially because the software (the model) was obtained late, and time to evaluate the model computational demands was required before making the best determination of computer requirements. After the software was obtained in May 2002, a temporary machine had been borrowed to evaluate computational demands of running the biomechanical model.

Scientific & Technical

1. An improved baseline was developed for the model.
   The baseline was redefined as the resultant walking pattern and was found to be more realistic and thus a better approximation or representation of normal human walking. The primary improvements were reduction in exaggerated leg motions. This improved model performance was obtained during the initial evaluation and preparation for the sensitivity analysis. During that process, minor modifications were made to the model to gain familiarity with model performance and to determine how best to implement the sensitivity analysis. The understanding gained about the relationship between model performance and specific variables during this process facilitated this model improvement. The model consists of nearly 800 equations and nearly 200 variables, making the relationship between a single model parameter and model performance a complicated one. It is worth noting that fundamental model control structures were not

changed in order to gain the additional congruence of model and normal human walking noted above. Rather, the changes (improvements) were interpreted as more a fine-tuning. Thus, the stability and robust performance of the original model remain intact.

2. Model benchmarking

The model performance compared favorably to that tabulated in existing and laboratory (internal) normative human walking databases. Performing this assessment was also essential to familiarize the project staff with the model. A gait analysis report was generated detailing model performance. The model performance was fundamentally similar to normal human locomotion. Many parameters fall within published as well as our laboratory (i.e. internal) normative ranges. Some specific similarities and differences are now reported.

Temporospatial footfall parameters – a measure of gross walking performance – were reasonable for the model walking speed and anthropometrics. The vertical ground reaction forces (GRF) showed the familiar double humped shape as well as appropriate magnitudes. For a walking speed of 1.1m/s, the noted peak GRF greater than body weight was appropriate. During midstance, the body accelerates downward resulting in a GRF less than body weight. This was also reproduced in the model. The loading rate of the leg from heelstrike to footflat was slightly higher than observed in normal human barefoot or shod walking. Progression of the center of pressure under the foot during stance phase was qualitatively similar to that seen in human walking. The timing of muscle activation corresponded reasonably well. The overall phases and range of motions of the joints were also strongly similar. One exception is that of the hip and knee, both of which showed excessive flexion during swing phase. The stance phase knee also showed noticeably less flexion during the loading phase. The joint kinetics showed qualitative similarities to published and internal data, but noticeably more differences than the kinematic data. These data were more difficult to quantitatively compare to normative ranges due to unavailability of published age, gender and speed matched joint moment data. Further model assessment and evaluation along the lines detailed above will be reported in the IDA or acceleration based analysis.

3. Sensitivity analysis and interpretation has been completed (see Appendix III)

The model was found to not be overly sensitive to any one group of parameters and thus is suitable for the simulation of muscle weakness and compensatory response without any further modification. It was necessary to determine the robustness of the model performance as our group did not have prior operational experience with this specific model; regardless, these data had not been published in sufficient detail in previous literature describing this type of model. Thus, it was a necessary analysis to be run before simulating muscle weakness and evaluating the compensatory process. More detailed results and how the sensitivity analysis was run follow.

The model demonstrated stability of performance over a wide range of changes in each parameter group. Changes are reported in terms of percent difference from the baseline condition. The model was capable of producing stable locomotion over a range of changes from 70 to 182% in the sensory group. Similarly, the neural group could be changed from 56-145%, the posture control group from 87-170%, and the movement generator group from 90-120%. An overview of sensitivity analysis methodology follows.

Five groups of parameters from four major subsystems of the model were identified from the nearly one hundred parameters and variables used in the model. The parameters in the neural interconnectivity, sensory feedback, posture control, and movement generator subsystems were selected. The final parameter was the "nonspecific input" – thought to be related to an integrated higher level (brain) parameter. The range of values of these parameters for which the model could perform the walking task successfully was determined by incrementally varying each group of parameters in approximately 5% intervals while all the other parameters were held constant.

4. Intersegmental Dynamics Analysis (IDA) based analysis
Codes to access and rearrange Adams data formats to allow running of batch simulations to calculate IDA have been written and tested. IDA or induced acceleration analysis is the method to objectively and quantitatively calculate the effect of a single muscle force or net joint moment on body kinematics (acceleration). These codes were based on a different format from those previously developed in our lab (written in Matlab) that calculated accelerations directly from loads applied to the body because Adams does not calculate accelerations directly. Assessing the accuracy of IDA results was done in a manner similar to how it was originally done in our lab. The regenerated ground reaction forces (GRFs), joint accelerations, and pelvis forward accelerations were compared to the originally measured values.

Results of the initial IDA assessment of model performance showed that the model reproduces the vertical GRF in a manner similar, though not yet quantified, to that of a normal human during walking. Previous IDA analysis run in our lab was used to compare to the model breakdowns. These data could only be compared to internal or laboratory databases as these data have not been published in literature. Interpretation of the IDA analysis gave insight into the functional relationships between model muscle activation and model walking performance. This analysis also served as additional support to the similarity of the model control scheme to that of a normal human during undisturbed walking. Reconstruction of additional body degrees of freedom, such as joint rotation and pelvis translation, will further validate the IDA implementation and further support model similarity to human performance. This work will also lead directly to the calculation of the functional deficits database, as originally outlined. These IDA based analyses are still underway.

5. Perturbation analysis and interpretation have been partially completed
The ability of the model to respond in a realistic manner to a limited variety of perturbations suggests the appropriateness of the model for studying the effect of muscular weakness during a walking task. Responses were consistent with that expected based on knowledge of muscle roles during gait, interpretation of acceleration analyses, and anecdotal clinical cases. The model response to individual muscle weakness and to

major subsystem perturbation (sensitivity analysis) was interpreted with a perspective of characterizing the quality of the response compared to a human. The following is a brief overview of the preliminary interpretation of these analyses: The hip extensor weakness resulted initially in an increased step length. As the model appeared to be heading towards instability and collapse, it was able to rectify the instability and produce a shorter step length – more consistent with a learned response of an individual with hip extensor weakness. The contribution of the late stance/early swing knee flexor torque to braking of body forward propulsion was increased with knee extensor weakness. The knee extensor weakness resulted in an increased flexor torque. Surprisingly, there was little stance phase effect of weakened knee extensors. The ankle plantarflexor weakness results have not been fully understood yet. This work is in progress. Hip, knee and plantarflexor muscle weaknesses were modeled by reducing the rhythmic force coefficient. The resultant joint torques (hip, knee and ankle) were verified to be reduced. The responses of the model from the sensitivity analyses were also generally consistent with those that may be expected from qualitatively similar physiological situations, thus further supporting the appropriateness of the model response. Once the determination of model appropriateness has been made, a few normal subjects will be tested in order to compare to the model. Subject recruitment and testing, as defined in the human subject testing section of the protocol, is expected to begin in approximately 6 months.

KEY RESEARCH ACCOMPLISHMENTS:

- A total of 43 polio survivors and 63 controls have been enrolled in Study 1.
- Preliminary data analysis in Study #1 has begun.
- An improved baseline has been developed for the simulation model in Study #2.
- Sensitivity analysis of the model has been completed.
- Initial IDA assessment of model performance has been performed.
- Perturbation analysis and interpretation are underway.

REPORTABLE OUTCOMES:

- Talaty M, Patel M, Coulter T, Esquenazi A, Klein M. Physics-based Computer Simulation to Assist in the Understanding of Mobility Dysfunction and Rehabilitation. [Oral Presentation] Research in Progress Symposium, MossRehab Hospital, Philadelphia PA, September 2003.
- Talaty M, Patel M, Esquenazi A, Klein M. The Effect of Variation of Neuromusculoskeletal Model Control Parameters on Performance During Simulated Human Walking. [Paper Presentation] International Society of Biomechanics meeting, Sydney, Australia, July 2003.

- Patel M, Talaty M, Klein M, Esquenazi A. Evaluation of a Computer Model to Simulate Human Walking and Understand Compensatory Behavior for Muscle Weakness. [Poster Presentation] Research Recognition Day, Albert Einstein Medical Center, Philadelphia PA, May 2003.
- Patel M, Coulter T, Talaty M, Esquenazi A, Klein M. Development Of A Computer Model To Simulate The Effect Of Localized Muscle Weakness On Walking. [Poster Presentation] Annual Meeting of the Gait and Clinical Movement Analysis Society, Wilmington DE, May 2003.

CONCLUSIONS:

This section is not applicable at this time.

APPENDIX I

Analysis of Activity Patterns and Performance in Polio Survivors: An Analysis of Health Status and Activity Level in Polio Survivors Over Time

Inclusion Criteria

- Polio Survivor reporting new or worsening muscle weakness possibly due to late effects of polio
- Adult over age 45 with no history of polio but reporting some difficulty with mobility related tasks like walking or climbing stairs
- Must be able to ambulate a minimum of 3 feet with or without the use of an assistive device on a level surface
- Must be able to attend two study visits at the research office

Exclusion Criteria

- Kidney Failure needing dialysis
- Rheumatoid Arthritis
- Diabetes requiring medication for control
- Stroke (with sequelae)
- Cancer (other than skin) with current treatment
- Uncontrolled Seizures
- Uncontrolled High Blood Pressure
- Any cardiac or respiratory conditions that are not controlled
- Recent bone fracture (last 6 months)
- Spinal disc herniation or other back/neck disorders with new or worsening symptoms
- Polymyalgia rheumatica, systemic lupus erythematosus (SLE), muscular dystrophy, multiple sclerosis or similar conditions
- Any neuromuscular disorder (other than polio) such as Parkinson's disease
- Severe deformity or acute pain/swelling that would make doing the study tasks unsafe
- Any problem that makes it difficult to understand what is involved in the study or that may affect desire to perform the study tasks or that may make if difficult to do the study tasks
- Dementia or psychiatric illness

Determining Eligibility

Potential subjects are initially screened through a phone conversation during which subjects are asked to respond to a series of questions about medical conditions, polio history if applicable, and ability to do certain mobility related tasks. The questions asked are designed to elicit information specifically related to the inclusion and exclusion criteria identified in the informed consent form. This initial screening is reviewed to identify eligibility.

If exclusions are not identified and inclusion criteria are met, a subject history form (which includes medical history), and a polio history form are mailed to the subject for review and completion.

At the first visit, a research team member reviews the subject history and polio history forms completed by the subject to identify if any new information is provided that may impact eligibility.

Date:__________ Scheduled for: ___________

Meets/Does not meet criteria. (wants to stay in Dbase?----Yes___ No___) Packet sent on:________

DATE SCREENED________

SCREENING QUESTIONNAIRE [ACTIVITY MONITOR]

NAME:________________________________ D.O.B:______
STREET:______________________________ AGE:______
CITY:________________________________ GENDER:______
PHONE________________________

HOW DID YOU HEAR ABOUT THE STUDY:______________________________

1. HAVE YOU HAD POLIO?--Yes____ No____
   - AT WHAT AGE?___________
   - WHERE (WHAT BODY AREA) DID IT AFFECT YOU?
   - ____

2. HAVE YOU EVER BEEN TOLD YOU HAVE PPS?--------------------------Yes_____ No____

3. ARE YOU EXPERIENCING ANY NEW SYMPTOMS THAT MAY BE RELATED TO PPS? (for instance, increasing weakness or fatigue) Yes_____ No_____

   How long have you had the symptoms?______________________________

---

4. DO YOU HAVE ANY OF THE FOLLOWING?
   A. DIABETES---Yes____ No____
      IF YES, DO YOU TAKE INSULIN OR A PILL?

   B. ARM WEAKNESS THAT MAKES YOU UNABLE TO USE YOUR ARMS TO GET OUT OF A CHAIR? ---------------------Yes____ No____

   C. ANY DISEASE THAT CAUSES JOINT INFLAMMATION?--------Yes____ No____
      FOR EXAMPLE, RHEUMATOID ARTHRITIS

   D. ANY DISORDER SUCH AS
      FIBROMYALGIA---Yes____ No____
      SEIZURES--Yes____ No____
      PARKINSON'S DISEASE?--Yes____ No____
      MUSCULAR DYSTROPHY?--- Yes____ No____
      LUPUS (SYSTEMIC LUPUS ERYTHEMATOSUS)?--------------Yes____ No____
      MULTIPLE SCLEROSIS?---Yes____ No____
      POLYMYALGIA RHEUMATICA? --------------------------------- Yes____ No____
      HIGH BLOOD PRESSURE? ---Yes____ No____
         Do you take medication for your blood pressure?------------Yes____ No____

Date:________________ Name:________________________________

E. A HEART CONDITION THAT IS NOT CONTROLLED? -----------Yes____ No____
- DO YOU SUFFER FROM CHEST PAIN AT REST? ---------Yes____ No____
- HAVE YOU EVER HAD A HEART ATTACK ?--------------Yes____ No____
  - WHEN?_______________________________
- **DO YOU HAVE A PACEMAKER OR OTHER IMPLANTED DEVICE?**
  Yes_____ No_____

F. A BREATHING CONDITION THAT IS NOT CONTROLLED?-----Yes____ No____
- DO YOU USE OXYGEN?--------------------------------------- Yes____ No____

G. ANY PROBLEMS WITH YOUR BACK OR NECK?------------------ Yes____ No____

- WHERE?

- DO YOU KNOW IF YOU HAVE ANY HERNIATED DISCS?

  Yes____ No____

  WHERE? _____________________________________

- PLEASE DESCRIBE THE PROBLEM

- HOW/WHEN WAS IT DIAGNOSED?

- HAVE YOUR SYMPTOMS GONE AWAY?------------------Yes____ No____

- WHAT SYMPTOMS ARE YOU HAVING?
  (Any radiating pain in arms or legs? Any numbness or tingling?)

- ARE THE SYMPTOMS GETTING BETTER, REMAINING THE SAME, OR DO THEY SEEM TO BE GETTING WORSE?

H. CANCER THAT YOU ARE BEING TREATED FOR?----------------Yes____ No____

4. HAVE YOU HAD:

A. SURGERY IN THE LAST 6 MONTHS?----------------------------------Yes____ No____
- FOR WHAT / WHERE?_______________________________

Date:________________ Name:______________________________

B. ANY BROKEN BONES OR DISLOCATIONS IN THE LAST 6 MONTHS?-- Yes____ No____
   - WHERE?____

C. A STROKE?-- Yes____ No____

5. CAN YOU STAND UP FROM A CHAIR?--------------------------------------Yes____ No____

6. CAN YOU WALK?--Yes____ No____
   - ABOUT HOW FAR?
   - DO YOU USE A DEVICE TO HELP?------------------------------------Yes____No____
     - What kind? ________________________________
   - Do you wear an ankle or knee support of any kind? Please describe. (Which side?)
     - When do you wear it? When was the last time that you used it?

       ____

   - DO YOU WEAR BRACES?--Yes____ No____
     - WHAT KIND? ____________
     - WHEN?____

7. DO YOU HAVE ANY LIMB DEFORMITIES OR AMPUTATIONS *(NOT RELATED TO POLIO)*?--Yes____ No____

8. DO YOU HAVE ANY AREA OF SEVERE PAIN OR SWELLING?---------Yes____ No____
   - DOES THIS AREA MAKE IT SO YOU ARE UNABLE TO DO YOUR NORMAL TASKS?--Yes____ No____

9. DO YOU HAVE KIDNEY FAILURE OR RECEIVE DIALYSIS?-------------Yes____No____

10. HAVE YOU EVER BEEN TOLD YOU HAVE A MENTAL ILLNESS SUCH AS DEPRESSION, SCHIZOPHRENIA, BIPOLAR DISORDER, OR ANXIETY?--Yes____ No____

11. DO YOU HAVE ANY PROBLEM THAT WOULD MAKE IT DIFFICULT FOR YOU TO FOLLOW WRITTEN OR SPOKEN DIRECTIONS?----------Yes____ No____

PLEASE RATE YOUR ABILITY TO DO THE FOLLOWING ON A SCALE OF 0 (UNABLE TO DO) TO 4 (NOT DIFFICULT):

	RATING
1. WALK A ¼ OFA MILE (3-4 City blocks)	________
2. GO UP A FLIGHT OF STAIRS	________
3. STOOP DOWN (bending)	________

Date:________________ Name:______________________________

4. CROUCH (like a catcher in a baseball game) ________
5. KNEEL DOWN ________
6. PUSH A LARGE OBJECT (such as a bed or sofa) ________
7. CARRY 10LBS (across the room) ________
8. BATHE ________
9. DRESS ________
10. LIFT AND CARRY GROCERIES ________

- DO YOU HAVE ANY ALLERGIES?---Yes_____ No_____

  IF YES, PLEASE EXPLAIN?____

- ARE YOU ALLERGIC TO LATEX? Yes _______ No_____

  IF YES, DESCRIBE REACTION____

- ARE YOU PARTICIPATING IN ANY OTHER RESEARCH OR TREATMENT PROGRAM? IF YES, DESCRIBE.

- IS IT OKAY FOR US TO LEAVE A MESSAGE ON AN ANSWERING MACHINE SAYING THAT WE ARE CALLING FROM THE MOBILITY AND POLIO RESEARCH OFFICE?

- ARE YOU AN EMPLOYEE OF THE JEFFERSON/EINSTEIN HEALTH CARE SYSTEM?

- WHEN IS THE BEST TIME FOR US TO CALL YOU?

  ____

APPENDIX II

Subject Initials:_____ Subject ID:_____

Subject History

- Date of Birth: ___________ Sex: M____F_____ Race: ____________
- Are you a veteran? Yes _____ No _____
- What hand do you write with? Rt_____ Lt_____ Both_____
- When walking, which foot do you step forward with first? Rt_____ Lt_____ Both_____
- List Allergies to Medication, and the type of reaction you have if you know: ____________

____

- List all medications you are taking (including over-the-counter and herbal medicines), the dose and the frequency:

MEDICATION	REASON FOR TAKING	DOSE / FREQUENCY

- Have you been diagnosed or treated for any of the following conditions:

____Heart problem ____Osteoporosis ____Asthma

____Angina ____Arthritis ____Emphysema

____High blood pressure ____Thyroid ____COPD

____Cholesterol ____Cancer ____Glaucoma

Subject Initials:____ Subject ID:____

- Please list any other medical conditions you are aware you have, and when you learned of the condition.

1______________________ 3______________________

2______________________ 4______________________

- List all surgeries that you have had and the approximate date.

1.______________________ 4.______________________

2.______________________ 5.______________________

3.______________________ 6.______________________

- List all broken bones that you have had. Please include how the bone was broken and when.

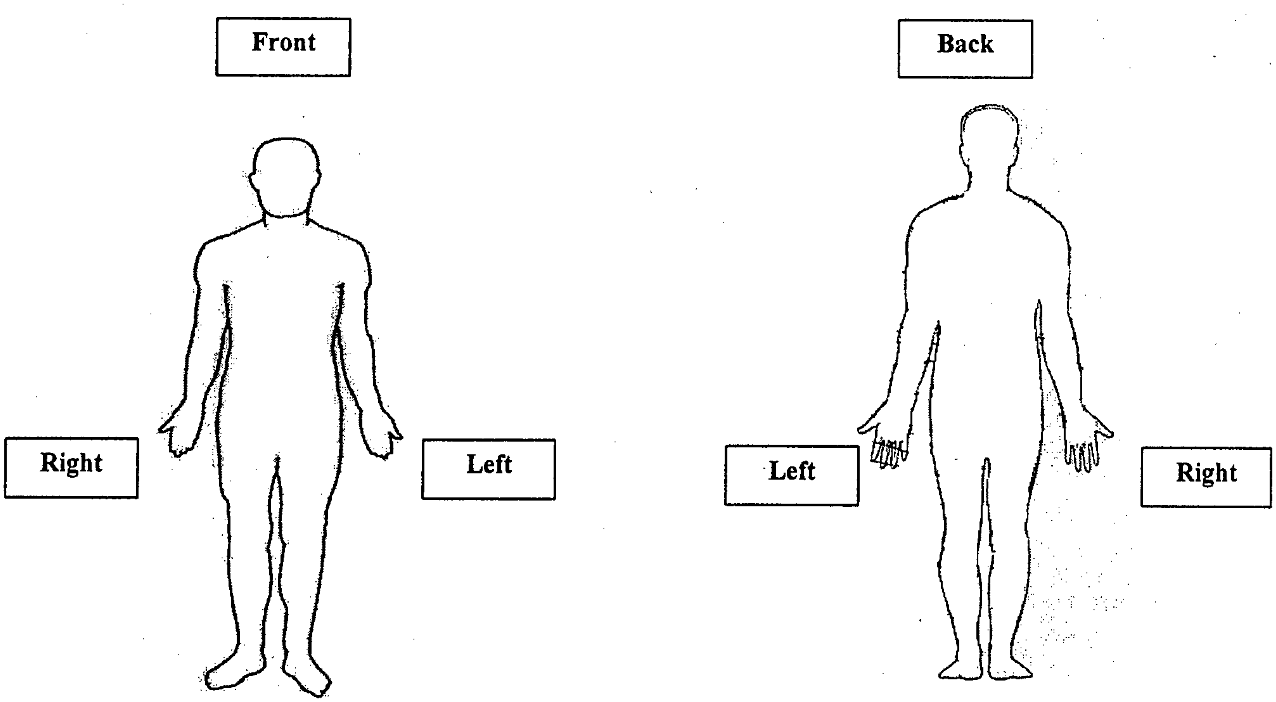
____

____

____

- If you are a woman, have you gone through menopause? Yes____ No___
  - If yes, are you taking hormone replacements? Yes____ No____

- On the 'body' below, please shade in any areas that you feel pain or discomfort on a regular basis.



*For the areas that you marked, are you taking any medication? Yes____ No____

Subject Initials:____ Subject ID:____

- Do you smoke? Yes____ No____
  - If yes, what is the average number of packs you smoke in a week? ________
- Do you care for someone on a regular basis (such as a child or dependent adult)?

  Yes____ No____
  - If yes, how often? ________________________
- Do you help another person(s) with his or her daily activities? Yes ____ No _____
  - What things do you help with? ____

  ____
  - On average, how many hours per week do you help? __________
- Does anyone help you with your daily activities? Yes ___ No ___

  What things if any, do you need help with? ________________________________

  ____
- Does someone help you with indoor household chores? Yes ____ No _____
- Does someone help you with outdoor household chores? Yes ____ No _____
- Do you receive pay for work? Yes _____ No______
  - Are you paid for working: Full time (30-40hrs/week) ____

    Part-time(less than 30 hrs/week) _____

    Not working for pay _____
  - What type of work do you do? ____
- Do you do volunteer work? Yes_____ No_____
  - If yes, what is the average number of hours you volunteer in a month? _________
  - What type of volunteer activities do you do? ______________________________
- Do you currently drive? Yes ____ No____
- Do you use / wear eyeglasses or contact lenses? Yes____ No____
  - Are you able to read newspaper print? Yes_____ No_____

- Do you have any trouble hearing? Yes____ No____
  - Do you use a hearing aid? Yes_____ No_____
  - Which ear? Lt _____ Rt_____ Both______

- Have you fallen in the last year? Yes ____ No_____
  - If yes, about how many times? __________________
  - Were you injured? Yes____ No____
    - Describe the injury. ____

- Have you had any trouble with dizziness in the last year? Yes_____ No____
  - If yes, please explain (how often, when etc) _________________________________

- Please rate the quality of your sleep in the last 2 weeks:

  ______very restful ______somewhat restful _____a little restful ____not restful at all

  - How does this compare with your usual sleeping pattern?

  _____less restful than usual _____about the same ______better than usual

- Please rate your stress level in the last 2 weeks:

  ______not very high ______ somewhat high ______high ______very high

  - How does this compare with your normal stress level?

    ______lower than normal ______about the same ______higher than normal

- What is your current marital status?

_____Single	_____ Married
_____ Living in a marriage-like relationship	_____ Widowed
_____ Divorced or Separated	_____ Other

Subject Initials:_____ Subject ID:_____

- What is your current living arrangement?

_____ Live alone _____ Live with friend(s)

_____ Live w/family member(s) _____ Other

  - How many people live in your household? _________

- Do you have a pet(s)? Yes_____ No_____
  - What kind of pet(s) do you have? ___________________________________
  - Who takes care of the pet(s)? ______________________________________

- What is your highest level of education?

  _____ Less than high school graduate

  _____ High school graduate or equivalent

  _____ Some college education

  _____ Completed college degree

- When you walk, do you use an assistive device? Yes_____ No_____
  - If yes, what kind? _______________
  - When do you use the device?
    - _____Always _______Inside home _____Outside home ______Long distances only

- Can you rise from a chair without using your arms for assistance? Yes _____ No______

- Can you go up a flight of stairs without using a handrail? Yes_____ No______
- Can you go up a flight of stairs using a handrail? Yes ____ No_____

- Can you go down a flight of stairs without using a handrail? Yes _____ No _____
- Can you go down a flight of stairs using a handrail? Yes _____ No _____

Subject Initials:_____ Post-Polio History Subject ID:______

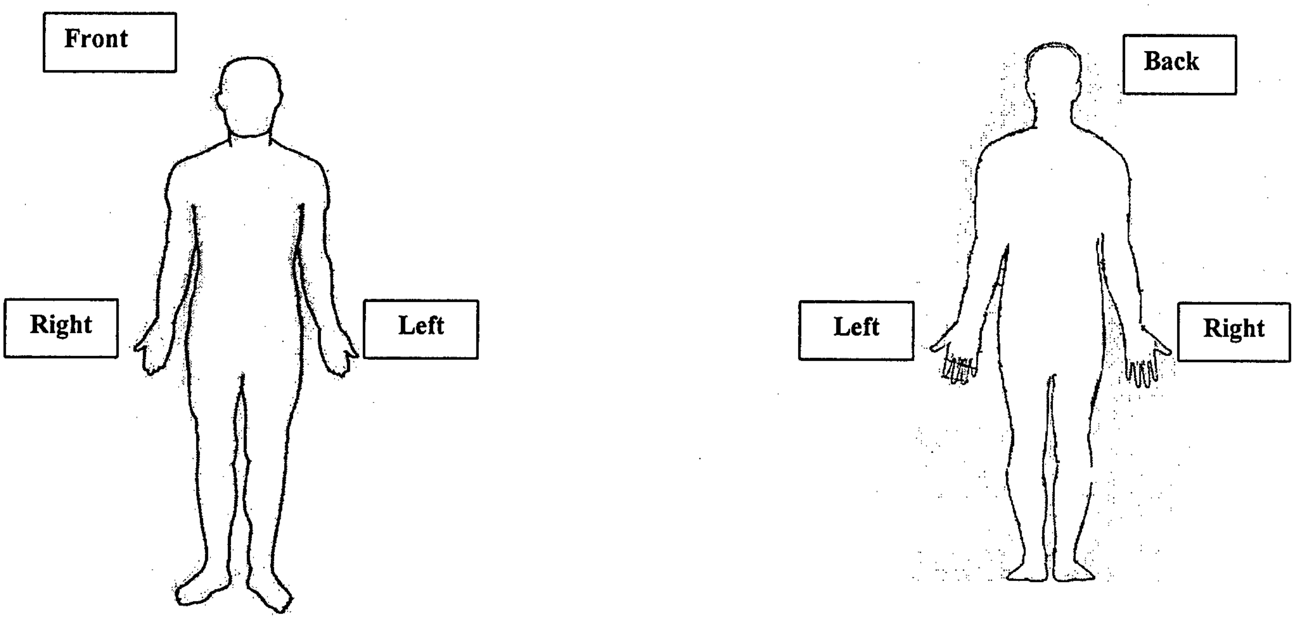
1. At what age did you have polio? _____
2. Which type of polio did you have?

   Bulbar _____ Spinal ______ Both _____ Unsure ______

3. Did you have to use an iron lung? Yes ___ No ___
4. On a scale of 0 – 10, please rate how severely you were initially affected by polio. ('0' is no affect; '10' is severely affected)

   RATING: ______

5. Please shade on the 'body' below where you were affected.



6. Do you wear braces now? Yes ___ No ___ If yes, how many hours each day? _______

   What type of braces? Rt short leg ___ Lt short leg ____ Back ____ Other ____________

   Rt long leg ___ Lt long leg ____ Neck _____

7. Do the braces lock at the knee? RT: yes___ no___ n/a ____

   LT: yes___ no___ n/a ____

8. When did you start wearing braces?

____

9. Do you have an insert or special shoe to correct a leg length discrepancy? Yes ___ No ___

If Yes: Left _____ Right ____

10. Do you use any devices such as:

Cane:	yes	no	Wheelchair:	yes	no
Crutches:	yes	no	Scooter:	yes	no
Walker:	yes	no	Other:	yes	no

- If you use a cane, which hand do you use it with? Left Right Both
- If you use crutches, which arms do you use them with? Left Right Both
- If you use a wheelchair or scooter, when do you use it?
  (always, distance walking, shopping, etc.)

____

____

11. Has a doctor ever told you that you have Post Polio Syndrome (PPS)? ___Yes ___No
    - When were you told this? ____________

12. Are you experiencing any new symptoms that may be related to PPS? (such as increasing weakness or fatigue?) No____ Yes____
    - If yes, what symptoms are you having?________________________________

13. How many years passed from the time you initially had polio to the time you first experienced symptoms of Post Polio Syndrome (PPS)?

_____ Up to 5 years

Not having any symptoms____

_____ More than 5 years, but less than 10 years

_____ More than 10 years, but less than 15 years

_____ More than 15 years, but less than20 years

_____ More than 20 years

14. On a scale of 0 – 10, please rate how severely you are currently affected from polio symptoms. ('0' is no affect; '10' is severely affected)

RATING: ________

Since the onset of Post Polio Syndrome (PPS), have any of the following health problems been experienced?

If yes, circle a number from 1 – 10 that indicates how severe the problem is for you (1 is very mild; 10 is very severe)

		SEVERITY RATING									
New weakness in 'affected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
New weakness in 'unaffected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Tiredness in 'affected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Tiredness in 'unaffected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Muscle twitching in 'affected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Muscle twitching in 'unaffected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Muscle cramping in 'affected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Muscle cramping in 'unaffected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Pain in 'affected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Pain in 'unaffected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10

Since the onset of Post Polio Syndrome (PPS), have any of the following health problems been experienced?

If yes, circle a number from 1 – 10 that indicates how severe the problem is for you
(1 is very mild; 10 is very severe)

		SEVERITY RATING									
Change in size of 'affected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Change in size of 'unaffected' muscles • Location:	NO	1	2	3	4	5	6	7	8	9	10
Breathing difficulty	NO	1	2	3	4	5	6	7	8	9	10
Problems concentrating	NO	1	2	3	4	5	6	7	8	9	10
Swallowing problems	NO	1	2	3	4	5	6	7	8	9	10
Sleeping problems	NO	1	2	3	4	5	6	7	8	9	10
Depression	NO	1	2	3	4	5	6	7	8	9	10

Subject Initials: ________

Subject ID: ________

Date: _______

Visit #: _______

FATIGUE SCALE

FATIGUE SEVERITY SCALE QUESTIONNAIRE

DURING THE PAST WEEK, I found that:	Strongly Disagree						Strongly Agree
1. My motivation is lower when I am fatigued.	1	2	3	4	5	6	7
2. Exercise brings on my fatigue	1	2	3	4	5	6	7
3. I am easily fatigued	1	2	3	4	5	6	7
4. Fatigue interferes with my physical functioning	1	2	3	4	5	6	7
5. Fatigue causes frequent problems for me	1	2	3	4	5	6	7
6. My fatigue prevents sustained physical functioning	1	2	3	4	5	6	7
7. Fatigue interferes with carrying out certain duties and responsibilities	1	2	3	4	5	6	7
8. Fatigue is among my three most disabling symptoms	1	2	3	4	5	6	7
9. Fatigue interferes with my work, family, or social life	1	2	3	4	5	6	7

SUBJECT ID:________ SUBJECT INITIALS:_________ DATE:__________
VISIT:__________

SICKNESS IMPACT PROFILE (SIP 68)

Directions *(Please Read Thoroughly)*:

Daily life consists of a number of activities. Sometimes you can carry out all of these activities. It is possible, however, that you don't do a number of these activities in the usual way as a result of your health or physical limitations. You may have stopped doing some activities altogether, you may do the activities differently, or you may do the activities for a shorter period of time. We are interested in the types of changes in your activities that are related to your state of health. These changes may have occurred only recently, or they may have taken place some time ago.

Read the statements one by one and determine if they are applicable to your situation today. Also determine if they apply to you because of your state of health. If this is the case, mark an **X** in front of the statement and go on to the next one. For example, one of the statements is:

___ I stay home most of the time.

If this statement is true and related to your state of health, mark an **X** in front of it.

_X_ I stay home most of the time.

You mark an **X** even if you have stayed home as a result of your state of health for a longer period of time. Don't mark an **X** if you're spending most of your time at home because you want to read a book, or because the weather is bad. In this case you are at home a lot because of the weather or because you want to read a book, not because of your health. You should mark an **X** next to statements that concern changes that have occurred recently or some time ago.

In short, mark an **X** next to statements that:

- Describe your **SITUATION TODAY**
- Are true as **A RESULT OF YOUR HEALTH**

Please do not consult others on any of the statements. We are interested in what you think.

You may begin filling out the questionnaire. Read the statements carefully and determine if they describe your situation and if they are related to your state of health.

Sickness Impact Profile (shortened version)
A. F. de Bruin, J.P.M. Diedericks, L.P. de Witte, F.C.J. Stevens, H. Philipsen

SUBJECT ID:________ SUBJECT INITIALS:_________ DATE:__________
VISIT:__________

Please mark an **X** *next to statements that:*

- Describe your **SITUATION TODAY**
- Are true as **A RESULT OF YOUR HEALTH**

1. ___ I get around in a wheelchair.
2. ___ I get dressed only with someone's help.
3. ___ I do not move into or out of bed by myself. I am moved by another person or technical aid.
4. ___ I stand up only with the help of another person.
5. ___ I do not fasten my clothing (for example, requiring help with buttons, zippers, shoelaces)
6. ___ I do not walk at all.
7. ___ I do not use stairs at all.
8. ___ I make difficult moves with help (for example, getting into or out of cars or the bathtub).
9. ___ I require assistance with some portions of bathing.
10. ___ I do not bathe myself completely (for example, requiring assistance with bathing)
11. ___ I do not have control of my bladder.
12. ___ I am very clumsy in body movements.
13. ___ I do not have control of my bowels.
14. ___ I feed myself with help from someone else.
15. ___ I do not maintain balance.
16. ___ I use a bedpan with assistance.
17. ___ I am in a restricted position all of the time.

SUBJECT ID:_________ SUBJECT INITIALS:_________ DATE:__________
VISIT:__________

Please mark an **X** *next to statements that:*

- Describe your **SITUATION TODAY**
- Are true as **A RESULT OF YOUR HEALTH**

1. ___ I go up and down stairs more slowly (for example, one step at a time or stopping often).
2. ___ I walk shorter distances or stop to rest often.
3. ___ I walk more slowly.
4. ___ I use stairs only with mechanical support (for example, a handrail, a cane or crutches).
5. ___ I walk by myself but with some difficulty (for example, limping, wobbling, stumbling, with stiff legs).
6. ___ I kneel, stoop, and bend down only by holding onto something.
7. ___ I do not walk up or down hills.
8. ___ I get in and out of bed and chairs by grasping something for support or by using a cane or walker.
9. ___ I stand only for short periods of time.
10. ___ I dress myself, but do so very slowly.
11. ___ I have difficulty doing handwork (for example, turning faucets, using kitchen gadgets, sewing, carpentry).
12. ___ I move my hands or fingers with some limitation or difficulty.

SUBJECT ID:________ SUBJECT INITIALS:_________ DATE:__________
VISIT:__________

Please mark an **X** *next to statements that:*

- Describe your **SITUATION TODAY**
- Are true as **A RESULT OF YOUR HEALTH**

1. ___ I have difficulty reasoning and solving problems (for example, making plans, making decisions, learning new things).
2. ___ I have difficulty doing activities involving concentration or thinking.
3. ___ I react slowly to things that are said or done.
4. ___ I make more mistakes than usual.
5. ___ I do not keep my attention on an activity for long.
6. ___ I forget a lot (for example, things that happened recently, where you put things, appointments).
7. ___ I am confused and start several activities at the same time.
8. ___ I do not speak clearly when I am under stress.
9. ___ I have difficulty speaking (for example, getting stuck, stuttering, stammering, slurring words).
10. ___ I do not finish the things I start.
11. ___ I have trouble writing or typing

Please mark an **X** *next to statements that:*

- Describe your **SITUATION TODAY**
- Are true as **A RESULT OF YOUR HEALTH**

1. ___ I am cutting down the length of my visits with friends.
2. ___ I am drinking less fluids.
3. ___ I am doing fewer community activities
4. ___ I am doing fewer social activities with groups of people.
5. ___ I am going out for entertainment less often.
6. ___ I stay away from home only for brief periods of time.
7. ___ I am eating much less than usual.
8. ___ I am not doing heavy work around the house.
9. ___ I do my hobbies and recreational activities for shorter periods of time.
10. ___ I am doing less of the regular daily work around the house than I would.
11. ___ I am cutting down on some of my usual inactive recreational activities and pastimes (for example, watching TV, playing cards, reading).

SUBJECT ID:________ SUBJECT INITIALS:________ DATE:__________
VISIT:__________

Please mark an **X** *next to statements that:*

- Describe your **SITUATION TODAY**
- Are true as **A RESULT OF YOUR HEALTH**

1. ___ I often act irritable towards those around me (for example, snapping at people, giving sharp answers, criticizing easily).
2. ___ I act disagreeable with my family members (for example, acting spiteful or stubborn).
3. ___ I have frequent outbursts of anger at family members (for example, striking at them, screaming, throwing things at them).
4. ___ I act irritable and impatient with myself (for example, talking badly about yourself, swearing at yourself, blaming yourself for things that happen).
5. ___ I am not joking with family members as I usually do.
6. ___ I talk less with those around me.

SUBJECT ID:________ SUBJECT INITIALS:_________ DATE:__________
VISIT:__________

Please mark an **X** *next to statements that:*

- Describe your **SITUATION TODAY**
- Are true as **A RESULT OF YOUR HEALTH**

1. ___ I am not doing any of the shopping that I would usually do.
2. ___ I am not going into town.
3. ___ I am not doing any of the house cleaning that I would usually do.
4. ___ I am not doing any of the regular work around the house that I would normally do.
5. ___ I stay home most of the time.
6. ___ I am not doing any of the laundry that I would usually do.
7. ___ I am not going out to visit people at all.
8. ___ I am getting around only within one building.
9. ___ I have given up taking care of personal or household business affairs (for example, paying bills, banking, working on a budget).
10. ___ I do not get around in the dark or in unlit places without someone's help.

Subject ID: ________ Tester Initials: ________ Date: ____________

Subject Initials: ________ Visit: ____________

Height: _________ Weight: _________ Monitor ID Number: ______________

Cadence Setting: ______________

STRENGTH EVALUATION:

	LEFT						RIGHT				
	DYNAMOMETER RESULT				MANUAL MUSCLE RESULT		DYNAMOMETER RESULT				MANUAL MUSCLE RESULT
	TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4			TRIAL 1	TRIAL 2	TRIAL 3	TRIAL 4	
KNEE EXTENSION											

MOBILITY EVALUATION:

First forward step taken with __________ foot

- Assistive device use: No Yes Type:______________________________________

	TIME	# of Steps Taken
1. Walk 30 Feet at Max Speed	__________	____________
2. Walk 30 Feet at Normal Speed	__________	____________

STEP LENGTH: _______________
(30ft / # of steps)

BODY MASS INDEX: __________
(wt in kg / ht in meters squared)

ACTIVITY MONITOR SETTINGS:

1. Quick stepping: Yes ___ No ____
2. Walking Speed: Normal ___ Fast ____ Slow ____
3. Range: Both extremes ____ Mod range____
   Rarely varies____
4. Leg motion: Fidgety ____ Norm____ Gentle_____

****Time Monitor Applied**: _______________*

Subject ID:________ Subject Initials:______ Date:________ Visit:_______

IN THE LAST 3 MONTHS:

1. Have you:

-Had any health problems?	yes ___ no ___
-Received treatment from a doctor?	yes ___ no ___
-Had any medical tests?	yes ___ no ___
-Had your medications changed?	yes ___ no ___
-Been hospitalized?	yes ___ no ___
-Been Injured?	yes ___ no ___
-Fallen?	yes ___ no ___

2. Has your activity level changed? yes ___ no ___
   - Are you doing more? yes ___ no ___
   - What is it that you are doing differently? ___________________________

COMPARED TO 3 MONTHS AGO:

3. How would you rate your ability to complete your normal daily activities?
   - **a.** When working (at a job or volunteering):

     Accomplish Less____ Accomplish the Same____ Accomplish More____
   - **b.** When doing leisure activities (at home or in social situations)

     Accomplish Less____ Accomplish the Same____ Accomplish More____

4. Are you able to do more now?
   - **a.** When working (at a job or volunteering):

     Yes, able to do more____ No change____ No, able to do less____
   - **b.** When doing leisure activities (at home or in social situations)

     Yes, able to do more____ No change____ No, able to do less____

5. When completing your normal daily activities, how would you rate the length of time it takes?
   - **a.** When working (at a job or volunteering):

     More Time____ Same Amount of Time____ Less Time____
   - **b.** When doing leisure activities (at home or in social situations)

     More Time____ Same Amount of Time____ Less Time____

Subject ID:________ Subject Initials:______ Date:________ Visit:_______

***COMPARED TO 3 MONTHS AGO*:**

6. Does it take less effort to complete your normal daily activities?

a. When working (at a job or volunteering):

Yes, less effort needed___ No change___ No, more effort needed___

b. When doing leisure activities (at home or in social situations)

Yes, less effort needed___ No change___ No, more effort needed___

7. When completing your normal daily activities, do you require:

a. When working (at a job or volunteering):

Fewer rest periods___ Same amount of rest periods___ More rest periods___

b. When doing leisure activities (at home or in social situations)

Fewer rest periods___ Same amount of rest periods___ More rest periods___

8. During your normal activities, in terms of the length of rest periods that you take when working (at a job or volunteering), on average are they:

Shorter___ The Same Length___ Longer___

9. During your normal activities, in terms of the length of rest periods that you take when doing leisure activities (at home or in social situations), on average are they:

Shorter___ The Same Length___ Longer___

10. How would you rate your ability to deal with stress / stressful situations?

Not Able to Deal as Well___ Deal the Same___ Able to Deal More Effectively___

11. How would you rate your ability to relax?

More Able to Relax___ Relax the Same___ Not Able to Relax as Well___

12. Do you find you have more energy to participate in social activities with family, friends, or neighbors?

Yes, more energy___ No change___ No, less energy___

***COMPARED TO 3 MONTHS AGO*:**

13. Has your physical ability to complete your normal daily activities changed?

Improved___ Stayed the Same___ Worsened___

14. Has your emotional ability to cope with every day issues changed?

Improved___ Stayed the Same___ Worsened___

15. Has your ability to participate in social activities changed?

Improved___ Stayed the Same___ Worsened___

16. Has your endurance level changed?

Improved___ Stayed the Same___ Worsened___

17. Has your strength changed?

Improved___ Stayed the Same___ Worsened___

Date ____________________ Subject ID _________

SELF-PERCEPTION AND FUNCTION QUESTIONNAIRE

For questions 1-7, please choose one of the following responses and write the appropriate number in the space following the question.

1 - Strongly disagree
2 - Disagree
3 - Agree
4 - Strongly agree

1. Things keep getting worse as I get older. ______________
2. I can do just about anything I set my mind to. ______________
3. I have as much pep as I had last year. ______________
4. If I want something, I go out and get it. ______________
5. I feel that as I get older I am less useful. ______________
6. I am as happy now as I was when I was younger. ______________
7. I am a go-getter. ______________

For each statement/question below, please circle the response that is most appropriate for you.

8. As I get older, things are (better/worse/same) than I thought they would be. Better Same Worse

9. How much do you feel lonely? Not much A lot

10. How satisfied are you with your life today? Satisfied Not satisfied

11. How would you describe your health status?

Improving Remaining about the same Declining

Date ____________________ Subject ID ________

12. Which of the following things are you physically able to do? (Please place an X by each of the things you can do.):

_______ Heavy work around the house (shoveling snow, washing floors, etc.)

_______ Work at a full-time job

_______ Ordinary work around the house

_______ Walk half a mile

_______ Go out to a movie, to church, to a meeting, or to visit friends or relatives

_______ Walk up and down stairs

Best It Could Be

Worst Possible

Please place a mark on the line above that best represents your current state of health.

Subject Initials:__________

Subject ID: __________

Date:________

Visit #: ________

FATIGUE RATING / DAILY

Each day, after you have finished your normal activities, please rate your level of fatigue on a scale of 0 – 10.

'0' INDICATES NO FATIGUE, '10' INDICATES THE WORST FATIGUE POSSIBLE

DAY / DATE OF WEEK	FATIGUE RATING

Subject Initials:__________ Date:__________

Subject ID: __________ Visit #: __________

PAIN LOG / DAILY

*Please rate the average level of pain you felt each day on a scale of 0 – 10.
'0' indicates no pain, '10' indicates the worst pain imaginable

DAY / DATE OF WEEK	SITE OF PAIN	HAVE YOU FELT THIS PAIN BEFORE?		*PAIN RATING 0 - 10	WHAT ACTIVITIES CAUSED THIS PAIN?	HOW LONG DID THE PAIN LAST?
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			
		Yes	No			

Subject ID: ________

Subject Initials: ________

Date: ________

Visit #: ________

ACTIVITY LOG

Day / Date of Week	Estimated Time Monitor On / Off	Activity	For Each Activity, Estimate Distance Walked (in blocks)
	Time ON: Time OFF: Time ON: Time OFF:		
	Time ON: Time OFF: Time ON: Time OFF:		

APPENDIX III

THE EFFECT OF VARIATION OF NEUROMUSCULOSKELETAL MODEL CONTROL PARAMETERS ON PERFORMANCE DURING SIMULATED HUMAN WALKING

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Keywords: Sensitivity analysis, Neuro-musculoskeletal model, Compensatory behavior

Abstract. *The sensitivity of the walking performance of an established neuromusculoskeletal model to four major parameter groups was assessed to evaluate its robustness and response characteristics. Variables from the sensory system, the neural interconnectivity, the movement generator, and the postural controller groups were individually varied and the simulations rerun for each case. The range over which the parameters were varied was dictated by when the model could no longer walk. Overall, the model was robust in that it could walk over moderate to relatively large ranges of changes in each parameter group. The model was least sensitive to changes in the sensory parameters, exhibiting stable walking over a range of –30% to + 82% of the baseline value. It showed a large range for the neural interconnectivity and postural controller variables. It showed stable walking for the smallest range, -10% to +20% for the rhythmic or movement controller variable. Continued testing will further elucidate the characteristics of the model responses and its similarity to that of a human. Intersegmental dynamics (or "induced acceleration") analysis will be used to assess how the model performance strategy differs from that of normal human walking. This may also be used to refine how the model responds.*

1. Introduction

Understanding the compensatory or adaptive response of an individual with pathology is a critical component to evaluating treatment options. The clinician often aims to identify the primary deficit when a patient presents with a complicated gait deviation. As a simple example, a patient with stiff knee gait may circumduct the leg in order to gain sufficient swing clearance necessary for limb advancement. However, the primary deviation is at the knee, not the hip. In more complicated cases, this identification may not be as obvious. Compensation often occurs naturally and automatically. Computer simulation of a musculoskeletal model that responds in a manner similar to a patient can be used to clarify the impairment-disability relationship and may allow for the prediction of outcomes of clinical interventions, such as strengthening or a brace, to improve mobility.

Demonstrating that a model both walks and reacts to pathological changes like a human remains one obstacle to increasing the utility of computer simulation (Neptune 2000; Talaty 2002b). Such validation is a challenging task (van den Bogert, 1999). Application of the simple rule of, "If it walks like a duck, quacks like a duck,... then it must be a duck!" may be a useful guide to assessing the validity of a computer model. Relating this premise to a walking model, simply establishing that a model *walks* like a human does not ensure that it would *react* in the same way to pathology or resulting muscle weakness (Winter 1990; Wright 1999). "Quacking like a duck" or responding like a human may be a more critical evaluation criterion. Devising some well-conceived experimental paradigms to assess similarity of model response to that of a human can be informative. Congruence can lend to support that the model can be used to learn about the human system. This is a critical step, yet is not frequently reported in literature.

Sensitivity analysis is a necessary step to model evaluation and can provide a glimpse into model behavior as well. A model may be considered robust if it can perform as desired in the presence of noise or partially disrupted or altered inputs. Sensitivity analysis can assess robustness and whether the model performance depends strongly on one or more parameters. In the latter case, the values of these parameters should be established with maximum accuracy. Robustness is virtually a prerequisite in a study that aims to perturb a model as is the present case. Our intention is to introduce patterns of weakness to the model and learn about its compensatory response to that weakness profile. The behavior of a computer model depends on the scheme used to control it. The walking performance or behavior of the present model emerged out of the interaction of neural elements, mechanics of the body, and environmental constraints.

2. Methods

The model consisted of explicit representations of neural circuits and musculoskeletal elements. There were 8 segments, 7 joints, 20 muscles, 14 neural oscillators, and a two-part viscoelastic foot. It was capable of producing stable upright walking that closely resembled normal human gait after a few steps of transient walking. Several key parameters such as the force of the rhythm or movement generator and of the posture controller, the level of sensory feedback, and the amount of interconnectivity between neural elements were perturbed in a sensitivity analysis to characterize model behavior.

2.1 The Model

A model has been implemented in which stable locomotion emerged through the global entrainment among the rhythmic activity of the neural system, the rhythmic movements of the musculo-skeletal system and the environmental constraints (Taga 1995). This approach was based in dynamical systems theory. The model was comprised of a distinct albeit considerably simplified neural system and a musculoskeletal system. There were separate subsystems incorporating sensory afferents, posture, and rhythmic movement. The main relationship that gave rise to the neural excitation was represented by a differential equation [1].

$$\tau_i \frac{d\dot{u}}{dt} = -u_i - \beta f(v_i) + \sum_{j=1}^{14} w_{ij}^0 f(u_j) + u_o + Q_i + S_i \quad [1]$$

The neural excitation signal (u_{i+1}) was a result of the integration of inputs from the neural excitation of the previous instant (u_i), inhibition (v_i), neural interconnectivity (w_{ij}), a constant tonic input (u_o), neural oscillator coupling (Q_i), and sensory inputs (S_i). In short, the core neural system was represented by a group of simple oscillatory circuits called rhythm or central pattern generators (CPGs). CPG performance was modulated by sensory receptors and higher neural centers to produce relatively robust and flexible control.

The model could walk upright for an indefinite number of steps. Model walking closely resembled human walking. Compared to published normative data, the model showed reasonable progression and temporo-spatial parameters, joint ranges of motion and torque, and muscle activation (Table 1). Variational or sensitivity analyses was performed to understand the effect of parameter variation on performance and to clarify model behavior.

Variable	Model Value
Height	1.8m
Weight	70kg
Walking speed	1.1 m/s
Stance/swing ratio	64%/36%
Stride length	1.3m
Hip range of motion	15° ext./60° flex
Knee range of motion	3° ext./ 78° flex
Ankle range of motion	27° pf / 42° df

Table 1. Anthropometric and steady state gait temporo-spatial and joint kinematic values of the model.

2.2 Sensitivity Analysis

The model sensitivity was tested by varying key parameters from each subsystem over the stable range of performance of the model. The following parameters were varied: strength or weight factors of the sensory input, the neural interconnectivity, the posture controller, and the rhythmic force or movement controller. Parameters in each subsystem were varied one at a time. However, each group of parameters was varied en masse. For example, when the sensory parameters were varied, the rhythm and posture controller and the neural interconnectivity variables were maintained at their baseline values. However, all eight variables (sensory input strengths) that gave rise to the actual the sensory contribution (S_i in equation 1) to each of the fourteen neurons were simultaneously varied. A limit in a sensitivity parameter (group) was assumed when the model became unstable and fell over. Steady state model performance in each altered condition was compared to the steady state baseline performance. Steady state walking was usually obtained after about five to eight seconds of simulation time. Several whole body and joint temporal, kinematic, and kinetic parameters were evaluated to assess the effect of parameter changes on model performance. Stride length, gait period, swing peak knee flexion, and peak knee torque were reported in this abstract.

3. Results

3.1 Sensory Parameter

The model was capable of walking with changes in this parameter over the range of 70% to 182% (Figure 1). Peak swing phase knee flexion and torque increased the strength of the sensory input beyond the baseline. The gait cycle time and stride length decreased. The reverse was found as the sensory parameter was decreased, except the gait period did not change. At the minimum, the model fell forwards.

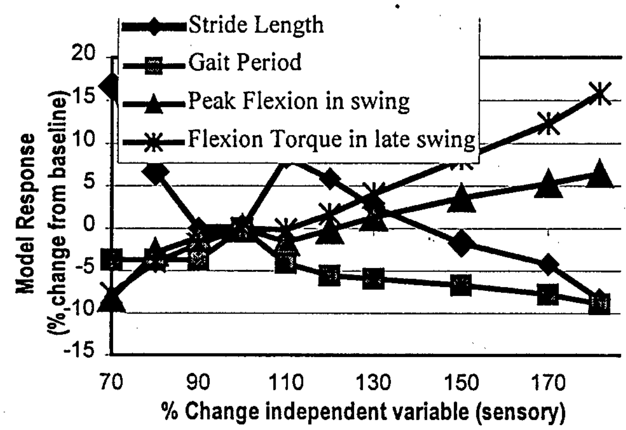

Figure 1. Model responses to changes in sensory parameter.

3.2 Neural Interconnectivity Parameter

The model could walk with changes in neural interconnectivity over the range of 56% to 145% (Figure 2). At minimum values of neural interconnectivity the model fell backwards; at maximum values, it fell forwards.

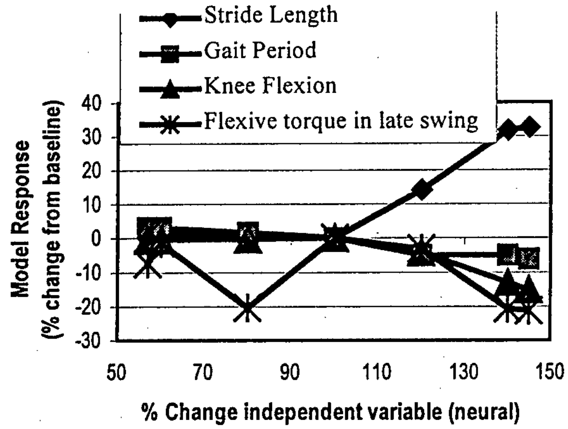

Figure 2. Model responses to changes in neural interconnectivity parameter.

3.3 Posture Controller Parameter

The model was capable of walking with changes in this parameter over the range of 87% to 170%. Stride length increased with this parameter up to about 110% after which it leveled off. The gait period showed a similar change. Knee flexion decreased as this parameter decreased.

3.4 Movement Controller Coefficient

The model was capable of walking with changes in this parameter over the range of 90% to 120%. An increase in this parameter caused a monotonic increase in the active knee torque, terminal stance phase knee flexion, and walking velocity where as the gait period decreased.

4. Discussion

Characterizing the model performance as its parameters varied helped to establish its robustness. The sensitivity analysis was one approach to characterizing model performance. The parameter variations were mathematical in nature. Each variable group was incremented and decremented by fixed percentages until the model could no longer walk in a stable manner. Interpretation of the results (model behavior) was done with a mathematical as well as a physiological perspective.

4.1 Interpretation of the Sensitivity Analysis

Model performance was less sensitive to changes in the sensory coefficient than to those in any of the other parameter groups. This variable group had the largest range over which the model performance was stable. Perhaps this coefficient was less critical to performance than the others. However, when the sensory coefficients were entirely eliminated (set to zero), the model was incapable of walking. This concurs with a commonly held belief in CPG theory (Grillner 1985). The model was more sensitive to decrease in sensory input rather than increase. Decreased knee flexion torque and swing phase knee flexion resulted in inadequate clearance and a forward fall. A minimum level of sensory input was required to cross the threshold of the neurons in the CPG to produce the muscle torque necessary for stable walking. Increasing the sensory input strength considerably resulted in hypersensitivity and instability.

The model was robust to changes in neural interconnectivity, as evidenced by the large range over which stable walking was produced. As the values decreased, the lower extremities seemed to progress further than the trunk, eventually resulting in the trunk not keeping up with its support base. The model fell backwards. Neural interconnectivity was a mechanism for synergy among joints in the kinetic chain. Each leg joint received excitation from the other ipsilateral joints. The trunk received only input from the hips, and was perhaps more susceptible to isolation due to reduction in the connectivity parameter. As connectivity increased, the step length increased while knee flexion torque and knee flexion decreased resulting in improper toe clearance and a forward fall.

The model was more sensitive to decreases than to increases of the postural parameter. The postural controller acts mainly on extensor muscles and is thought to be responsible for maintaining a stable upright posture. The decreased mid-stance knee flexion observed with reduction of the postural parameter provided a mechanism for loss of stability and the fall of the model.

The model was the most sensitive to the coefficient of the rhythmic or movement controller. This parameter was directly related to active muscle force output during dynamic motor task performance. The narrow range (30%) for which the model walked was surprising. Patients with more profound weakness can walk. In this analysis, all these "strength" coefficients were simultaneously reduced, not just that of a single muscle group. Single muscle weakness analyses are underway.

There can be several levels on which to assess the computer simulation of a model. The ideal simulation would produce a walking pattern that was within the normal range and would perform in a manner exactly as a human would when perturbed. Only a similar walking pattern between the model and the human is not sufficient to establish that the model responds or adapts like a human. Establishing a similar control parameter profile may lend more support to human-like responses. For example, EMG or joint moments have been compared to normal human profiles. Intersegmental dynamics analysis (IDA) or induced acceleration can provide another level of comparison of model control and performance. This analysis determines the specific contribution of joint moments or muscle forces to specific motions during gait. This analysis can help to evaluate where the model control and control strategy may differ from that of a normal human. Because IDA more directly relates a control parameter to performance, it may also guide some adjustment or refinement of the existing model control scheme.

5. Conclusions

The model was robust or not overly sensitive to changes in all of the tested variables. This lends support to use of such a model for perturbation analysis – for example to explore the effect of muscular weakness. It also suggests that the inherent structure (mechanics and information integration) provide considerable stability to model performance.

The complexity of the existing model makes defining the priorities by which it responds difficult. The rationale behind other simulation approaches is perhaps more evident. A tracking-based control scheme prioritizes obtaining a specific trajectory or walking pattern. An optimization-based control scheme prioritizes obtaining a specific cost – such as minimizing energy. In the present model, walking emerges from a complex series of interactions between subsystems and the environment. These subsystems are modeled after known and speculated principles in human physiology. The ability of the model to walk as similarly to a human as it does suggests much of the necessary information was included and it was done so in a successful combination. The factors that give rise to compensation or adaptive responses in humans are complex and not well understood at present. Including more of the known aspects of human neuromuscular physiology may inherently account for some of the critical factors in the compensation response. Further testing the response characteristics of the present model can lend additional support to its utility for learning about human compensatory response in the presence of pathology.

6. Future Work

The model performance in other similar functional tasks to walking or in constrained. walking tasks will be assessed. This will elucidate another aspect of the appropriateness of the model response.

Acceleration analysis can provide the basis for the addition of another control scheme. It is likely impossible to intuitively estimate what contribution a particular muscle or joint moment will have on a remote segment or joint. The use of computer models is essential to objectively determine the role of muscle during walking (Zajac 2003). It is planned to add a scheme that explicitly incorporates the potential or ability of each muscle group to compensate for specific muscle weaknesses. Such a scheme may either be layered on top of the existing control scheme or may simply replace it. Preliminary work has shown in normals that hip and knee moments contributed to restore ipsilateral ankle deficits in a manner consistent with the potential of each joint moment to assist (Talaty 2002a). This same work has shown that the acceleration components can be very sensitive to small changes in body orientation.

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