HUMAN PERFORMANCE MULTIMETER: INVESTIGATION OF THE FOURTH GENERATION PROTOTYPE

by

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ABSTRACT

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The focus of this thesis is the development and investigation related to the newest prototype version of the Human Performance MultiMeter (HPMM). Version 4 is a technologically advanced, compact, portable and self-contained unit that is the result of an on-going effort in human performance measurement covering a 25 year history at the Human Performance Institute involving the conception, development, and evaluation of over four hundred different measures. Such measurements are applicable in areas ranging from medical diagnosis and rehabilitation to ergonomics and athletic proficiency.

The work included verification of the functionality of a new hardware platform, modification of previously developed test procedures and software algorithms for the new hardware, and new development for selected aspects of the system. Steadiness measurement has been expanded to include components based on two axes of rotational rate and the formulation of a four degree of freedom composite steadiness measure. Five generic tests incorporated in this version of the HPMM were used in an experimental study with 20 healthy adult volunteers to evaluate reliability and validity. Selected performance capacities of specific body subsystems (isometric grip strength, visual-hand response speed, index finger tapping speed, upper extremity neuromotor channel capacity, and hand-arm steadiness) were measured in a test-retest design: . Test-retest reliability was found to be very good ($r > 0.75$) for most measures. Results were compared to those from HPMM v3.0 and to results from pre-established, validated data acquired over the years from laboratory based instruments. Good agreement was noted and expected patterns supporting validity were observed.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

CHAPTER 1

INTRODUCTION

The Human Performance Institute has been the seat of research in the area of the measurement of a wide range of performance capacities. These include human sensory, information processing, neuromuscular and cognitive systems. For these measurements, a modular set of laboratory instruments have been developed. Collectively known as the Human Performance Capacity Measurement System (HPCMS), this can be viewed as a set of items that can be combined in a variety of ways to realize various different, application specific "human performance capacity measurement systems" (Sriwatanapongse, 2002).

In 1992, the challenge to develop what was termed a Human Performance Multimeter (HPMM) was identified. The HPMM was conceived as a portable, compact version of the HPCMS that would exploit emerging microprocessor, sensor, and other technologies. Several preliminary versions of the HPMM were designed and evaluated, with each subsequent design converging to an optimization of functionality, packaging, and measurement performance. This thesis represents the latest step in the evolution of the HPMM. It focuses on verification of the functionality of a fourth generation hardware platform, modification of previously developed test procedures and software algorithms for the new hardware platform, new development for selected aspects of the system, and rigorous experimental evaluation of a selected set of HPMM's performance capacity measures in human subjects.

1.1 Human Performance Capacity Measurement Research Background

Over 25 years of development effort encompassing 400 different measurements acquired through 20 different, continuously evolving instruments has resulted in the Human Performance Capacity Measurement System (HPCMS) (Kondraske, 1990). Human Performance Measurement, Inc. of Arlington, Texas provides modular instrument packages representing these instruments. The philosophy associated with this technology is such that this laboratory-based Human Performance Capacity Measurement System (HPCMS) may be viewed as a flexible set of items (procedures, modules, *et cetera*) that can be combined in various ways to realize a wide variety of different, application-specific "human performance capacity measurement systems." (Human Performance Measurement Inc. 2004). To provide perspective, a brief review of this development history is warranted. Potvin, Tourtellotte, Syndulko and colleagues dating from the late 1960s were pioneers of work that raised the need for quantification of what they termed "neurologic function" (Potvin *et al*, 1985). They investigated and established many basic methods and the first subset of devices for a "neuro-function laboratory," and addressed key issues of measurement quality such as reliability, validity, age and gender effects, and subject motivation. Their laboratory was applied exclusively as a research tool, primarily in clinical trials of new drugs aimed at progressive neurologic diseases such as Parkinson's disease and Multiple Sclerosis.

At the University of Texas at Arlington, a first generation computer based system was developed by Kondraske as a basis of his dissertation research (Kondraske, 1982). A new set of specially designed instruments were incorporated, which were capable of implementing modified versions of test items in the neuro-function laboratory as well as new items which added to the scope of the system. The characterization of *individual* subjects (in contrast to "group study" research applications) was emphasized as the primary need upon which research and design were focused. Attention was given to items which could be viewed as being "application independent" or those items which reflected more intrinsic characteristics (e.g., strength, speed, *et cetera*) of human subsystems. This is in contrast with approaches that focus on performance of the individual in relatively complex higher level tasks such as gait or activities of daily living. Kondraske has argued (Kondraske 1990, Kondraske 2000b) that there is a finite (albeit large) set of the more intrinsic characteristics associated with a fairly well defined set of subsystems as opposed to the infinite variety of the higher level tasks in daily life. A modular measurement system architecture which facilitated expandability was introduced based on factors such as:

1) The complexity of the human system and the recognition that there are more measures that will be required.

2) Each patient (or subject) is unique. It is thus likely that, for optimal characterization, a unique subset of the tests and measurements would be used in a

given situation for a given patient (or patients of different types). This also allows us to view the system as a flexible measurement 'toolbox'.

3) It is highly desirable to integrate results acquired from several modules to facilitate clinical interpretation.

Largely with funding from the National Institute for Disability and Rehabilitation Research, second and third generation laboratory-based Human Performance Capacity Measurement Systems were developed. The "application-independent" philosophy and basic architecture facilitated expansion of the basic system to include modules which meet broader needs within rehabilitation (2nd generation). Common denominator measurement issues across these diverse disciplines that were often hidden or confounded by different terminologies and traditions were identified by simultaneous involvement of different professionals which make up rehabilitation teams (not only neurologists, but also orthopedists, physical and occupational therapists, and others). The name given to describe the system consequently changed from "neuro-function laboratory" to "sensori-motor performance laboratory," and ultimately to "human performance".

New issues were now to be explored given that the basic toolbox had now grown in power. The Big Picture context was analyzed, leading to questions such as what these measurements meant in larger scenarios, such as "an individual's ability to memorize an identification number" or "live alone independently". The issue that was now discovered was that despite efforts to quantitatively characterize capacities, there was still a lack of a conceptual model in this field. General Systems Performance

Theory and the Elemental Resource Model (Kondraske, 1995; Kondraske, 2000b) were introduced to address this and a number of related issues in human performance. The Elemental Resource Model is a hierarchically organized model based on a small but robust set of systems performance constructs, was introduced to address the need for a broad unifying understanding of the human system and its relationship to tasks..

These conceptual developments led to subtle but important transformation of several major classes of measures in the HPCMS, as well as a clearer definition of performance measures and the protocols under which they were acquired (Sriwatanapongse, 2002).

1.2 The Human Performance Multimeter

Recent advancements in sensor, low-powered electronic, microprocessor and battery technology motivated the vision of a device that integrates the functionality of laboratory-based performance capacity measurements instruments into a handheld, portable model that is also compact, accurate and relatively low-cost. Making the analogy in terms of concept, portability, and general purpose utility to the ubiquitous digital multi-meter, the Human Performance MultiMeter (HPMM) represents an effort in this direction. The HPMM was first conceptualized in 1992 (Kondraske, 1992). Areas that would benefit from such a device include neurology, emergency medicine (i.e., status screening), sports medicine, rehabilitation, battlefield medicine, space medicine, gerontology, field sobriety testing, toxicological screening and industrial medicine (e.g., alcohol/drug abuse).

A series of sequential developments and investigations were undertaken, which are detailed in other documents (Kondraske, 2005). Early work involved the assessment of the types of measurements that were feasible and what their requirements were, as well as the kind of trade-offs that might be required given the system's compactness and portability. Short-term memory, visual and auditory information processing speed, neuromotor channel capacity in manual speed/accuracy tradeoff tasks, visuomotor coordination, speech motor control, isometric strength, vibratory sensation, steadiness and speech motor control fall within the measurement candidates considered for this instrument. For a subset of this functionality, individual subsystems were designed, prototyped and bench evaluated. Two successive total system designs have been fleshed out, partially implemented and tested by students of the Electrical Engineering Senior Capstone Design classes taught by Dr. Kondraske at the University of Texas at Arlington in 2000.This resulted in a preliminary realization of what was termed "version 3" of the HPMM hardware platform. As part of a subsequent thesis (Sriwatanapongse, 2002), a set of software algorithms covering a subset of the desired measurement functionality were developed and tested with version 3 of the HPMM. A set of five so-called "generic test algorithms" were implemented and tested experimentally with 18 subjects for reliability and validity. Generally good reliability was obtained. Moreover, most results compared favorably with lab-based instruments. This work included considerations and development of a basic HPMM "operating system" as well. Version 3 was still very much a "bench top" realization; it was not yet packaged in the form of a portable multi-meter.

In another Electrical Engineering Capstone Design class taught by Kondraske during the fall of 2002, student teams developed a next generation hardware platform for the HPMM. This included a more advanced processor, important changes to packaging and architecture. A display with greater capacity and the incorporation of touch screen technology, and many other changes aimed at improving the basic platform to support performance capacity measurements. The result of this effort was the preliminary version 4 HPMM hardware platform. Operating system and test algorithms from the version 3 effort (Sriwatanapongse, 2002) were not implemented and only very basic functional testing of the platform and its key subsystems was completed as part of this effort.

Table 1.1 Summary of HPMM Development Milestones.

Year	Milestone/Development Status	Context
1992	First Conceptualization of HPMM	Small Business Innovative Research Grant Proposal to NASA. G.V. Kondraske, principal investigator
1996	V1.0 Design and Prototype: Based on 1992 proposal. Definition of key operational modes, partial functionality, limited implementation of specific tests, bench top realization (no packaging issues addressed).	Senior capstone design course in Electrical Engineering (spring semester).
2000	V2.0 Design and Prototype:	Senior capstone design course in Electrical Engineering (spring semester).
2002	V3.0 Design, Prototype, and Human Subject Testing: first formal human subject tests for five generic performance capacity tests	EE Masters Thesis, W. Sriwatanapongse
2002	V4.0 Design and Preliminary Prototype: More powerful processor, low power, increased display capacity, touch screen, enhanced sensors, "near final" portable packaging.	Senior capstone design course in Electrical Engineering (fall semester).

1.3 Objectives

The main goal of this thesis is to develop software components and define test and measurement protocols that will yield a prototype of the HPMM that can be deployed in clinical applications. Specifically, beginning with the earlier work (Kondraske 2001, Kondraske 2002) on the HPMM, the area that will be addressed is the upgrade of hardware and software (software being the majority area) onto a new system that yields faster results, is more portable, and conforms to newer technology standards.

The objectives of this thesis are to:

1) Review the architecture and functionality of previously designed instruments that were used in the same or similar areas. Analyze and enhance documentation of the design of the present version of the HPMM, strengthening the characterization of its various subsystems.

2) Adapt the current basic HPMM operating system software to the new hardware platform, incorporating a touch screen user interface and verify operation to support use in its Generic Test Mode.

3) Test and verifying performance of new hardware subsystems including high speed capacitive touch sensors, multi-axis inertial sensors, and the integration of a force sensor into the HPMM main unit packaging.

4) Propose a preliminary approach for the integration of dual-axis accelerometer measurements and dual-axis angular rate measurements to form a composite steadiness measure.

5) Review, revise as necessary, and implement test algorithms on the version 4 platform f for a selected subset of five HPMM generic tests: isometric grip strength, simple visual response speed, rapid alternating movement, upper extremity coordination and hand-arm steadiness.

6) Conduct a performance evaluation of the current version HPMM prototype in a complete “final package form” (i.e., not a bench set-up) and more specifically, then evaluate the reliability and validity of the five generic tests noted above in a population of healthy young adults.

7) Provide concluding thoughts and recommendations for future improvements, and future experimental work.

CHAPTER 2

BACKGROUND

2.1 HPMM System Concept and Design

The concept of the Human Performance MultiMeter (HPMM) is analogous to that of a digital multimeter used in a laboratory. Its purpose is to integrate as much functionality of laboratory based human performance measurement instruments as possible into one single, portable unit.

The platform design for this device is structured similar to that of a personal digital assistant (PDA). Apart from the integration of various sensor units that support performance measurements, the platform must present a graphical user interface that allows navigation of menus and accepts commands that will cause the system to perform the desired performance tests. Complete descriptions of the system design evolution, design process and current status are provided elsewhere (Kondraske, 2005a). This chapter presents a review and summary of the overall system concept and current design as well as background for a selected subset of performance capacity tests that are emphasized in this thesis.

2.2 System Concept

In version 4, the HPMM system consists of the main HPMM unit, the Remote Sensor Module (RSM), and the host PC (Figure 2.1). The main unit contains the LCD and touch screen as user interface. Menus can be navigated and options selected by the use of four touch sensitive 'buttons' on the touch screen. Selected basic sensors, including the force sensor and touch sensors array, are integrated into the main unit. Rechargeable batteries power this main unit with an on-board charging unit. An RS 232 serial port supports communication between the HPMM and other devices such as a host computer. The overall system concept includes two different test modes: (1) the Generic Test Mode and (2) The Protocol Driven Mode.

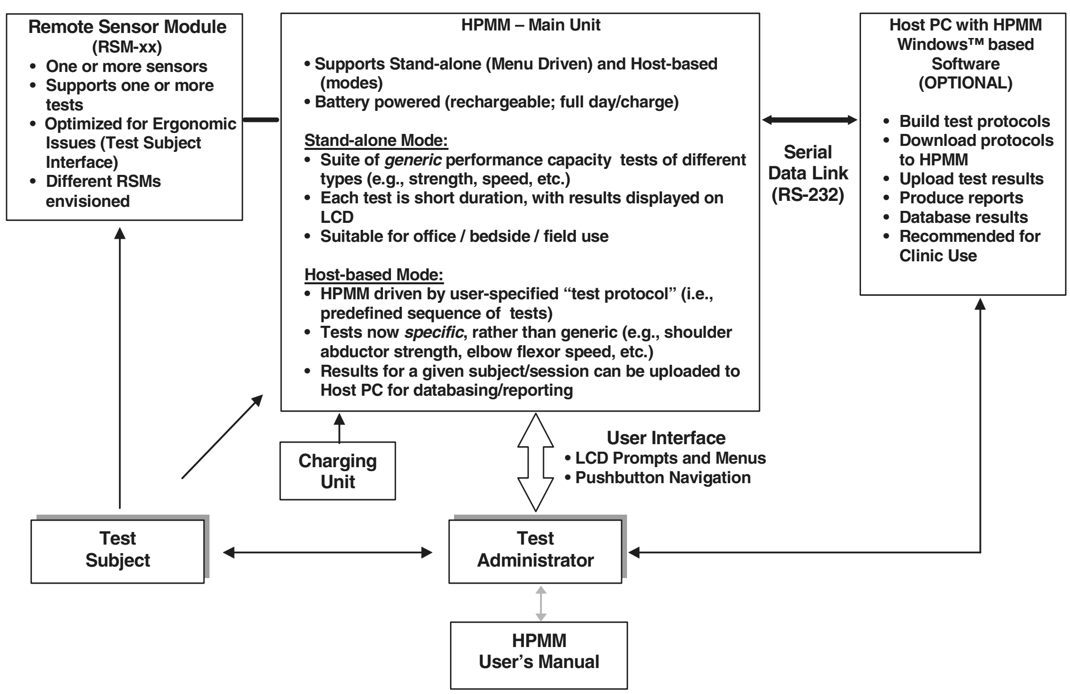

Figure 2.1 Major Features of the Overall HPMM System Concept.

In the Generic Test Mode, the unit is intended to be used as a stand-alone, general-purpose device that is capable of performing different "generic tests". Much like a digital multi-meter, which can measure "generic" electrical quantities such as voltage and resistance (and may specific voltages and currents can be measured), in the Generic Test Mode, the HPMM can be used to measure different "generic" performance capacities (for example, strength, angular movement speed, etc.). Similarly these could conceivably be applied to a number of different body subsystems for which the generic performance capacity is relevant. For example, strength capacity can be of interest for many different neuromuscular subsystems. Each test can be selected from the menu of such tests, executed, and the results are displayed on the shown on the screen for immediate observation and use.

The Protocol Driven Mode is considerably more sophisticated. A protocol is defined as a predefined series of performance capacity tests. In this mode, a "generic test" now becomes a "specific test". For example, "isometric strength" will now become "grip strength" (i.e., a particular body part is identified). Moreover, each result is labeled with its specific name and means must be provided for databasing of results. Several different functions must be implemented to support the protocol driven mode. For some of these, the HPMM main unit is linked to a host PC. Users can define one or more protocols (e.g., Parkinson Disease screening, Multiple Sclerosis screening, etc.) using host-based HPMM software and then download these protocols to the HPMM main unit. The HPMM can be used its normal portable fashion and the user can select from available protocols and then will be prompted through this series of tests. All results must now be labeled properly and recorded for subsequent upload to the host PC.

Prior to version 3, all HPMM hardware was contained in main unit. Beginning with version 3 ((Sriwatanapongse 2002), it was decided to include the capability to connect a remote module to the main unit, which is called a Remote Sensor Module. The concept of RSM facilitates expandability of the HPMM. Additional tests, which required extra sensors and hardware, can be added to the system by merely creating new RSMs. The RSM also increases portability, ease of operation, and measurement quality from an ergonomic perspective. The RSM can be placed on or attached to the selected part of the subject's body that needs to be tested, while the test administrator controls the tests and views test results from the main HPMM unit. The RSM may be customized to include certain sensor systems that specifically suit certain applications, which may lead to the use of the HPMM in broader application fields.

The host PC contains HPMM software that enables communication with the HPMM main unit and also performs higher level administrative functions associated with performance capacity measurement. It is only relevant for the Protocol Driven Mode. Communication is designed to be accomplished via a RS-232 serial link. As noted earlier in describing the Protocol Driven Mode, the host software lets the user create test protocols and download the test protocol to the main unit. Test results can also be uploaded from the HPMM, a report can be printed, and results can be stored in the PC. Host software will ultimately manage the results database and provide search and results analysis capability. The use of HPMM along with the host PC is suitable for applications that need to perform standard test protocols and store a large amount of test results database, such as in clinical use. In such settings, test protocols will be downloaded to the HPMM unit, and the HPMM will be disconnected and taken to the field site for operation. Once the testing is done, the unit can be brought back to upload the results to the host PC.

This thesis does not address any of the functionality associated with host-based operation. During development of versions 1 and 2, communication protocols were defined and preliminary versions of software were developed to explore the protocol driven mode. These functions have been given lower priority in favor of a focus on the fundamental performance capacity measurement capabilities of the HPMM.

2.3 HPMM Functionality and Architecture

Throughout the course of HPMM development, analyses were undertaken to determine the requirements for different subsystems (or functional units) that should be included in the HPMM architecture and how these subsystems should be included. This is driven by consideration of the possible measurement functionality that could be included as well as the ability of certain functional units to support implementation of more than one performance capacity test. A current result of this analysis and the status of each functional unit in the version 4 prototype is shown in table 2.1. As discussed in section 2.2, some of these basic functional units are located in the physically separate RSM unit.

Table 2.1 Basic functional unit candidates identified for eventual incorporation into the HPMM and status in the version 4 platform.

Functional Units	Status	Requirements and Other Specifications
Visual Display - Graphic	Included	LCD, low power, medium resolution. For user interface and warning / visual feedback mechanisms as part of selected tests.
Touch Screen	Included	User interface and sensor for cognitive tests
Visual Display - LEDs	Included	High intensity, high speed, 2000 mcd, red, 0.75 in diameter. Two units that can be independently controlled.
Force Sensor	Included	0-1120 Newtons, ±1 N resolution, tension and compression, integrate into main unit housing design
Microphone (with signal conditioning)	Included (RSM-1)	High sensitivity, directional.
Accelerometer(s)	Included (RSM-1)	At least 2 translational degrees of freedom desired. Measurement range uncertain.
Angular Rate Sensor(s)	Included (RSM-1)	Inertially-based, low drift, micro-miniature. Initially, only one degree of freedom was incorporated. Expanded to two degrees of freedom for version 4 to support steadiness measurement.
Vibration Generator	Not included	Piezoelectric (or electromagnetic)
Touch Sensor Array	Included	High speed, capacitive. Five touch sensitive regions up to and including version 3. Expanded to nine independent sensor regions to improve measurement capability and also enhance user interface.
Hand Temperature Sensor	Not included	High temperature change accuracy (≤ 0.1 ˚C)
Simple Sound Generator	Included	Piezoelectric, with ability to control pitch to provide different feedback "beeps" to subject and examiner.
Acoustic Stimulus Generator	Not Included	Support auditory screening and cognitive performance tests. high degree of calibration accuracy (±3dB).

Table 2.2 Matrix showing the assignment of different HPMM functional units to different HPMM functions and those generic tests included in version 4.

HPMM Functional Unit	General User Interface	Isometric Strength (GTA 1)	Visual Response Speed (GTA 2)	Rapid Alternating Movement (GTA 4)	Neuromotor Channel Capacity (GTA 5)	Steadiness (GTA 6)
Visual Display – Graphics	X	Prompts, Results	Prompts, Results			
Touch Screen	X	Test Progression	Test Progression			
Visual Display - LEDs			X			
Force Sensor		X				
Microphone (with signal conditioning)						
Accelerometer(s)						X
Angular Rate Sensor(s)						X
Touch Sensor Array			X	X	X	
Simple Sound Generator		Prompting	Prompting	Prompting	Prompting	Prompting

The user interface consists of a low-power LCD screen for displaying menus and test results, and a touch screen consisting of four 'buttons' for sending commands to the HPMM. Various stimulus units are also included. The LEDs, vibration generator, and sound generator provide visual, vibration, and audio stimulus respectively. Accelerometer and angular rate sensor are used to measure various parameters of human movement (see table 2.2).). These sensor subsystems will be placed on the tested body part of the subject. This requires the sensors to be as small and light as possible to have neglect effects on the test results. The touch sensors are used for sensing finger contact. These sensors must be highly sensitive for accurate measurement of finger movement on the sensors. The speed requirement is met by using capacitive touch sensors.

In addition to the fundamental hardware platform, an initial set of generic tests to be incorporated into the HPMM and their specifications has been identified (Sriwatanapongse 2002). These specifications are routinely reviewed and updated (Kondraske 2005a). Each of these generic tests draws upon different subsystems and is supported by a corresponding Generic Test Algorithm (GTA). In version 3, five different generic tests were implemented and evaluated (Sriwatanapongse 2002). The same generic tests, with selected enhancements, are now of interest in the context of the version 4 hardware platform. These are summarized in Table 2.2, along with the identification of the HPMM functional units included in version 4 hardware that are engaged in the implementation of each generic test.

Procedures characterizing how the basic functional units are to be employed to achieve the desired performance measurement capability have been closely modeled according to those used for existing, well-established laboratory-based tests. These are described in a separate Human Performance Institute technical document (Kondraske 2005a). Briefly, each test consists of a "test task" which is designed to isolate (to the degree possible) a given system at a given hierarchical level (i.e., basic element or generic intermediate level of the Elemental Resource Model (Kondraske, 1995)) and maximally stress that system along one or more dimensions of performance while time series data is collected. This data is processed in real-time to produce single number results representing availability of the isolated performance resource (e.g., visual information processor speed). This type of protocol is generally known as a maximal capacity test. Descriptions for the generic tests listed in table 2.2 and which are included as the subject of study in this thesis are provided in chapter 3.

2.4 Version 4 Hardware Platform Overview

As noted previously, a version 4 hardware platform for the HPMM main unit was designed as part of senior capstone design course. A block diagram indicating key features is shown in figure 2.3 and photos of the device are shown in figure 2.4 and 2.5. This platform serves as the basis for further work pursued as part of this thesis. Additional details regarding the hardware are provided in chapter 3.

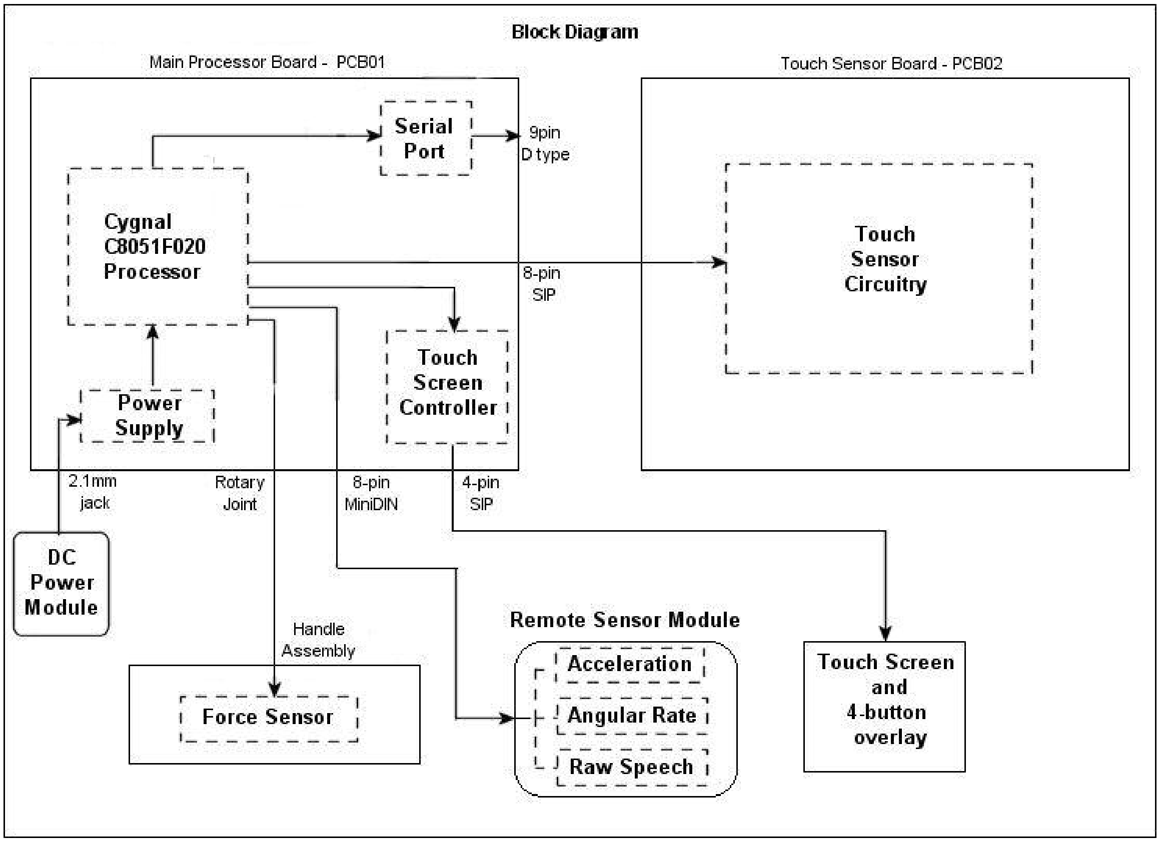

Figure 2.2 HPMM System Block Diagram.

Figure 2.3 HPMM System Top View.

Figure 2.4 HPMM System Bottom View.

The features that may be observed from the top view are the handle assembly that doubles up as the force sensor for isometric strength tests, the previously described LCD and touch screen with the button overlay, and the special RSM port. The bottom view shows the two high intensity LEDs, and the touch sensors, which are capacitive and have a much faster response than the touch screen buttons. The HPMM will also have a special rubber pad located on the bottom of the unit. This pad will be placed on the body part for force resistance test (quantitative manual muscle test) as shown in figure 2.5. The purpose of this pad is to alleviate discomfort to the subject's body during testing. In this test, the administrator applies force through the handle positioned on the top of the HPMM. The subject will try to maximally resist the force applied, while the administrator steadily increases the force until the subject can no longer resist.

The force sensor in the handle measures this resistance to the applied force and the processor will determine the maximum force resistance as the strength capacity result.

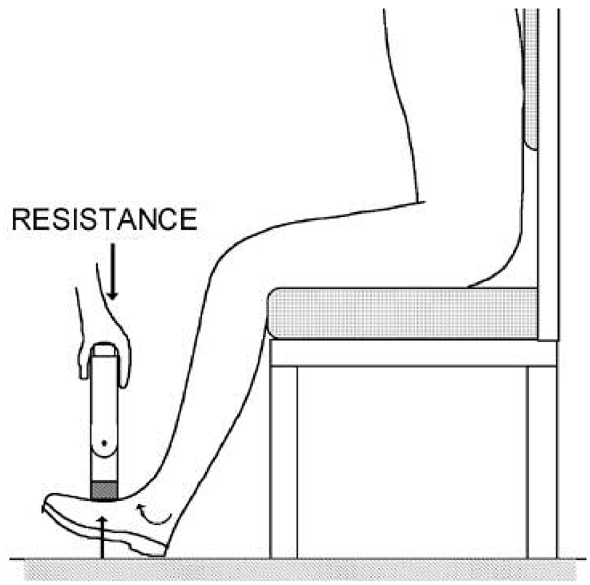

Figure 2.5 Resistance test (Quantitative manual muscle test).

2.5 Generic Performance Capacity Tests

In the General Purpose Test Mode, the unit is intended to be used as a stand-alone, general-purpose device that is capable of performing sets of generic tests that are accessed at random. For example, a neurologist could use the device while making rounds and decide on-the-spot that a particular measurement is of interest. One of the generic tests (e.g., isometric strength capacity) – which is really a test "type" - can be selected. The user will make the "generic test" a "specific test" by choosing, for example, which neuromuscular subsystem to test. This is like deciding which voltage to measure in a circuit. The procedure will be carried out and the result will be shown on the screen. If desired, the neurologist could record the results manually.

A wide array of generic tests is envisioned for the HPMM. At present, this thesis focuses on five generic tests. These are all designed to be consistent with concepts of General Systems Performance Theory and the Elemental Resource Model for human performance (Kondraske 2002). Furthermore, each of these is derived from tests incorporated into the laboratory-based human performance capacity measurement system (Kondraske, 1990). Each has also been implemented and evaluated to some degree in previous HPMM versions (Kondraske, 2005a, Sriwatanapongse 2002). Substantial changes have been incorporated into the hardware design that affects each of these tests; none have been implemented and tested on the current hardware platform. A review of the relevant background for each of these performance capacity tests follows.

2.5.1 Isometric Strength Test

This is perhaps one of the most generic of all the HPMM tests. It basically involves measuring the maximum force that a subject can generate or resist with a given neuromuscular subsystem (such as a shoulder abductor) or combination of such subsystems (as in gripping). A wide-range of instruments and approaches have been used for strength measurement (Smith 2000). Beasley (Beasley 1961) pioneered the measurement of isometric strength and provided numerous insights into reliability and validity of such tests.

The approach of interest is known as held-held dynamometry (Edwards and Hyde, 1977) and involves incorporating a force sensor, data acquisition, and processing algorithms into a paradigm commonly used by physical therapists called manual muscle testing. In manual muscle testing, the therapist uses his/her hands to push against or resist motions that would be produced by an isolated muscle group. They then must subjectively estimate the strength of that muscle group. Hand-held dynamometry attempts to make this process more objective and accurate, with greater measurement resolution. Kondraske and colleagues were among the first to computer-automate the measurement process (Kondraske et al 1984) and have more than 20 years of experience with the design of optimized sensors and processing algorithms within the context of the HPCMS. A recent review of hand-held dynamometry (Kolber and Cleland 2005) concluded that this approach is generally reliable and a useful improvement to manual muscle testing.

Version 3 of the HPMM (Sriwatanapongse 2002) utilized the grip strength sensor currently used in the HPCMS. This is modified in version 4 to better integrate the sensor into the latest packaging concept and to allow for testing of the strength of muscle groups other than those associated with hand grip.

2.5.2 Simple Response Speed Tests

This test is representative of a class of tests commonly referred to as reaction time tests (Kondraske and Vasta, 2002). These tests involve responding "as quickly as possible" to some type of stimulus (e.g., visual, auditory, etc.) in some specified manner (e.g., moving a body segment). The stimulus is required to have a low information load and thus requires minimal cognitive processing. This gives rise to the characterization of the test as "simple", which also distinguishes it from other tests of information processing speed.

This class of tests has long been used to characterize subjects with neurologic diseases such as multiple sclerosis and Parkinson's disease (Potvin et al, 1985) and individuals who have sustained traumatic injuries such as concussions or other head injuries. It is also useful in detecting and characterizing neurologic side-effects of drugs (Callaghan et al 1997). It is therefore desirable to incorporate this type of test into the HPMM as it has been.

2.5.3 Rapid Alternating Movement Performance Test

Halstead introduced a maximal performance finger-tapping speed test as one component of a basis for discriminating the intelligence of individuals (Halstead, 1947). This test has been incorporated into a popular neuropsychologic test battery known as the Halsted-Reitan battery (Vega and Parson, 1967). In neurology, the finger-tapping test is representative of a more general class of tests that have come to be known as rapid alternating movement tests. Kondraske and colleagues (Kondraske 1990) have adopted the Halstead paradigm for evaluation of performance involving other body segments, isolating reciprocal motions about the wrist, elbow, shoulder, and ankle.

The original finger tapping test has been shown to be a sensitive indicator in Parkinson's disease (Potvin et al, 1985), which is characterized in part by bradykinesia (slowness of movement), stoke (Prigatano and Wong 1997), and many other clinical situations.

The subject under test is instructed to tap their index finger “as fast as possible” for a prescribed time (e.g., 10 seconds). Historically, perhaps because of limitations in instrumentation and computing, only speed (in taps/sec) has been measured. Behbehani and Kondraske (1986) explored extracting additional parameters such as “time up” and “time down” from data acquired with electronic touch sensors. The most recent version of the HPMM that involved formal human studies (Sriwatanapongse 2002) incorporated a preliminary version of the rapid alternating movement test that measured speed, duty cycle, and consistency (variability of duty cycle). That prototype utilized touch sensor designs from lab-based systems. These were rather complex, custom designed circuits. More recently, special integrated circuits have become available with apparently suitable characteristics for human performance measurement applications. The current hardware design incorporates new touch sensor subsystems.

2.5.4 Upper Extremity Neuromotor Channel Capacity Test

In 1954, Fitts introduced a mathematical relationship between speed, accuracy, amplitude of movement, and target size for upper extremity tasks. This relationship, derived using basic information theory constructs of Shannon, has become widely known as Fitts' law (Fitts 1954). The mathematical statement of Fitts' law was defined originally only for translational motion in one dimension.

In Fitts' experiment, which was not intended to be a “measurement protocol” but rather an attempt to understand human motion, subjects held a stylus in their hand and were asked to move alternately between targets. Performance was controlled to achieve

96% accuracy; i.e., indicating that the system isolated (e.g., the upper extremity) was being maximally stressed. Movement time (t_m) was measured. Target width (W) and movement amplitude (A) were varied across a series of experimental trials with different subjects. He found that data fit the relationship that is now known as Fitts' law:

$$IP \text{ (bits/sec)} = -(1/t_m) \log_2(W/2A)$$

IP (dubbed by Fitts as the "Index of Performance") was shown to be relatively constant across a range of W and A values.

Kondraske and colleagues have adapted Fitts' experimental procedure for routine measurement of neuromuscular performance capacities (Potvin et al 1985, Kondraske 1990). A commercially available device that is part of the HPCMS, the Model BEP I (Human Performance Measurement, Inc, Arlington, TX) measures central processing and upper extremity neuromotor control performance capacities, including NMCC. This device incorporates six high-speed touch sensors along the front aspect of the unit for NMCC measurement. It has been used and evaluated by others with a wide range of subjects (Swaine and Sullivan 1992, Swaine and Sullivan 1993, Kauranen and Vanharanta 1996).

An NMCC test is performed by asking the subject to use his/her index finger and alternate between the narrower center sensors on left and right sides (40.6 cm separation) "as fast and as accurately as possible", thereby stressing the involved neuromuscular systems along speed and accuracy dimensions simultaneously. The first touch initiates a timed interval (10 sec) during which sensor contacts are recorded and categorized as "hits" or "errors". Separate R to L, L to R, and average lateral reach movement speeds and accuracy (percent) measures are computed. Note that it is not required that the subject achieve 96% accuracy. Rather, a more broad range (e.g., 60 - 98%) is allowed which facilitates more efficient administration in clinical contexts. Computations are performed that use the actual measured accuracy to determine an effective target width; i.e. that which would correspond to a 96% accuracy rate. This is then used in modified version of Fitts' relation to compute NMCC (bits/sec).

More recently, Kondraske used General Systems Performance Theory to approach Fitts' law from a different perspective (Kondraske 1999, Kondraske 2000). It was found that a near-perfect correlation between Fitts' Index of Performance and the product of movement speed and accuracy in hitting fixed width targets. An almost exact prediction was obtained by scaling the product using Fitts' task difficulty index.

Version 3 of the HPMM incorporated touch sensors for NMCC testing and a preliminary evaluation of the NMCC in this context was carried out (Sriwatanapongse 2002). The version 4 hardware platform incorporates new touch sensors and also divides the error regions surround the target regions into lateral and fore-aft components.

2.5.5 Steadiness/Tremor Test

Historically, interest has been in the measurement of the pathologic state of tremor and measurement of hand tremor with an accelerometer has been most prevalent (Potvin et al 1985, Takanokura and Sakamoto 2001). To reduce the loading effect associated with mounting an accelerometer on a hand, Kondraske developed a dual-axis, non-contacting capacitive displacement sensor for tremor measurement (Kondraske 1986). A newer version of this device has utilized as part of the HPCMS for nearly 20 years.

In recent years, micromachined sensor technology has reduced the size and mass of inertial sensors and has also greatly increased their durability and cost effectiveness. They are now considered attractive alternatives for tremor measurement in a portable device such as the HPMM. In version 3, a dual-axis accelerometer was employed. The packaging of the sensor chip and signal conditioning was crude, but results obtained were nonetheless encouraging (Sriwatanapongse 2002), providing reasonable agreement to those obtained with the capacitive displacement sensor when appropriate conversions were applied. A micromachined angular rate sensor was also incorporated into the version 3 architecture as part of the RSM. The intent was to use this for a future generic test termed movement speed. In the development of version 4 hardware, two such angular rate sensors were included in the RSM design. One commercial instrument for tremor measurement (Motus Bioengineering Corporation, Benicia, CA) incorporates a singe axis angular rate sensor (Moore, Ding, and Bronte-Stewart 2000). In version 4, the presence of four inertial sensors (two accelerometers and two angular rate sensors) will be exploited to more completely characterize the motions associated with tremor/steadiness.

2.6 Other Performance Requirements

In order for the HPMM to function effectively as a portable device, special consideration must be made for the power supply. The batteries for the HPMM would have to be small, but capable of providing enough power to operate the HPMM for a reasonable amount of time. A power supply design study (Hanson, 2000) suggested that the batteries should provide at least eight hours of operation. That should be sufficient for typical daytime operation in clinics. The batteries can then be recharged during nighttime. The current power supply design (Hanson, 2000) proposed the use of nickel cadmium (NiCd) rechargeable batteries for the HPMM. A compact, wall mounted A.C.-to-D.C. power module that is external to the HPMM is used to provide the power to the charging circuit when the batteries need to be recharged.

To optimize the battery power, another issue to consider is power management. Power management will be supported in hardware by providing the capability to turn each subsystem on or off by software. This is done with the use of low-dropout regulators (LDO). Power management implemented in software will control the power to each subsystem. Certain subsystems can be turned off when not being used. More detailed discussion and simulation model for the power supply can be found in (Hanson, 2000).

CHAPTER 3

IMPLEMENTATION

As noted, the version 4 HPMM hardware platform was designed under Dr.Kondraske's guidance as part of a one-semester senior capstone design course. This was an aggressive effort, leaving little time for testing of even the most basic hardware functions. Nonetheless, a relatively complete version of the main unit was fabricated and now provides the basis for careful scrutiny of the design, production of supporting documentation, and implementation of operating system and generic test algorithms on the new platform.

3.1 Hardware Implementation

A block diagram of version 4 was introduced in Chapter 2 (figure 2.1). Major subsystems are considered here in more detail to provide a basis for understanding the implementation of test algorithms. It is important to note that the HPMM is conceived of an expandable instrument. It is not simply that a well-defined set of functions exists and that hardware can be designed around these requirements. Rather, the goal is to realize a powerful, flexible hardware platform that allows for implementation of currently defined functionality as well as new functionality as it becomes defined. In this context, general features of the hardware platform are discussed as well as specific aspects pertaining to currently implemented functionality.

3.1.1 Microcontroller Core

The new HPMM 4 microcontroller core is the Cygnal (now Silicon Laboratories) C8051F020. This processor has an impressive collection of built-in peripherals and is a high-speed pipelined 8051-compatible microcontroller (up to 25 MIPS with a clock speed of 25MHz).. It contains a 12-bit 100ksps 8-channel ADC with on-chip Temperature sensor and an 8-bit 500ksps 8-channel ADC with analog multiplexer. On-chip memory includes 64kB of programmable FLASH memory and 4096 + 256 bytes of on-chip RAM. Five general-purpose 16-bit timers, an on-chip Watchdog Timer and Voltage Monitor and an on-chip oscillator complete the package.

The Code Memory consists of the 64 kilobyte FLASH memory, which can be rewritten repeatedly. This can be accomplished through code, using the MOVX command after certain Special Function Registers have been set and may also be programmed via a Joint Test Action Group_(JTAG / IEEE 1149.1) interface,

The 100-pin processor package option used in HPMM version 4 contains four additional ports over the 64-pin package and was selected to meet system requirements. To configure the processor I/O lines, it is necessary to use the processor's digital I/O 'crossbar' feature. Thus, the I/O pins as defined within the HPMM context are valid only when the crossbar is properly configured and enabled. Configuration is performed immediately after power-up as part of initialization and not altered during the course of system operation.

PIN I/O	P0								Crossbar Register Bits
	0	1	2	3	4	5	6	7	
TX0	●								UART0EN: XBR0.2
RX0		●							
SCK			●						SPI0EN: XBR0.1
MISO				●					
MOSI					●				
NSS						●			

Figure 3.1 Digital Crossbar Pin Assignments for the Serial Port and SPI Interfaces.

The two peripherals shown in the above table are automatically assigned to their port pins by the digital crossbar. This is achieved by setting bits 1 and 2 in the XBR0 register. The remaining port pins on the microcontroller will fall under the category of general purpose I/O pins (GPIO) because their functions are not assigned to them by the digital crossbar. Instead, they are assigned by the HPMM system designer. For example, port 0 pins 6 and 7 have been assigned the 'WAKE_UP' and 'EOC_TS' signal functions since they are connected to the /DAV and /PENIRQ signals on the touch screen controller. Table 3.1 shows all the port I/O pins used in the current HPMM system design, their functions and how they are assigned. The signals marked with an asterisk are assigned to the respective port pins using the digital crossbar. For the signals marked with a [1], signal assignments are context dependent; for the external memory interface they are assigned using the digital crossbar, for the LCD controller they are used as general purpose I/O pins.

Table 3.1 HPMM Port Pins and Descriptions

SIGNAL	PORT	PIN NOs.	DESCRIPTION
TX*	P0.0	62	Serial Communications – Transmit
RX*	P0.1	61	Serial Communications – Receive
SCK*	P0.2	60	SPI – Clock
MISO*	P0.3	59	SPI – Master In Slave Out
MOSI*	P0.4	58	SPI – Master Out Slave In
SS_μC*	P0.5	57	Microcontroller Slave Select
WAKE_UP	P0.6	56	PENIRQ signal from TSC2200
EOC_TS	P0.7	55	DAV signal from TSC2200
PWRE_COM	P1.3	33	ENABLE for serial communications LDO
PWRE_TCH	P1.4	32	ENABLE for touch screen LDO
PWRE_RSM	P1.5	31	ENABLE for RSM LDO
PWRE_LCD	P1.6	30	ENABLE for LCD LDO
POWER5V	P1.7	29	5V power subsystem enable
TCH_HOME	P2.0	46	HOME touch sensor
LF_C	P2.1	45	LEFT HOME touch sensor
LF_V	P2.2	44	LEFT VERTICAL touch sensor
LF_H	P2.3	43	LEFT HORIZONTAL touch sensor
RT_C	P2.4	42	RIGHT HOME touch sensor
RT_H	P2.5	41	RIGHT HORIZONTAL touch sensor
RT_V	P2.6	40	RIGHT VERTICAL touch sensor
RT_LED	P2.7	39	RIGHT LED
SS_TS	P3.0	54	SLAVE SELECT for touch screen
EOC_RSM	P3.1	53	End of Conversion (from TLV2553 ADC)
SS_RSM	P3.2	52	SLAVE SELECT for RSM
LF_LED	P3.5	49	LEFT LED
TCH_UIB1	P3.6	48	LEFT EXTREME touch sensor
TCH_UIB2	P3.7	47	RIGHT EXTREME touch sensor
CS_LCD	P4.4	94	Chip Select – LCD Controller
CS_RAM*	P4.5	93	Chip Select – External RAM
RD	P4.6	92	READ Signal - External RAM / LCD
WR	P4.7	91	WRITE Signal – External RAM / LCD
A0[1]	P6.0	80	C/D Signal on LCD Controller Address Line 0 on External RAM
A1[1]	P6.1	79	MD2 Signal on LCD Controller Address Line 1 on External RAM
A2[1]	P6.2	78	FS1 Signal on LCD Controller Address Line 2 on External RAM
A3[1]	P6.3	77	/RES Signal on LCD Controller Address Line 3 on External RAM
A4-A7*	P6.4-P6.7	76-73	Address Lines 4-7 on External RAM
A8-A15*	P5.0-P5.7	88-81	External RAM – Address lines
D0-D7*	P7.0-P7.7	72-65	Data Lines – External RAM / LCD

The ‘F020 has two on-chip analog-to-digital converters (ADCs). One is a 12-bit 100 KHz ADC and the other one an 8-bit, 500 KHz ADC. The HPMM is designed to use the internal 2.4 volt reference is used for these on-chips ADCs. The 9 channel, 12 bit,100 KHz ‘ADC0’ subsystem is used by the current HPMM prototype with the 2.4 volt internal reference. The ADC0 also has a programmable gain feature and eight out of nine channels are available for analog inputs while the ninth is internally connected to a temperature sensor output.

3.1.2 User Interface

The user interface includes a Liquid Crystal Display (LCD) module (Model AGM2412C, AZ Displays, Inc.) with a 240 x128 dot screen and both character and graphics capabilities. The module includes a Toshiba T6963C controller with 8k of memory, It is connected to the microcontroller through a set of I/O port pins (see table 3.1). At 10mm thick, this module is much thinner than screens used in earlier versions.

A touch screen (Model 95644, DYNAPRO) has been incorporated into the design of version 4 that eliminates the push buttons used in earlier versions for user input and provides new flexibility for user inputs associated with yet to be defined performance capacity tests. The touch screen is 117.2 mm x 88.4 mm x 1.3 mm and has a 0.5 mm horizontal resolution and 0.35 mm vertical resolution with the use of an 8-bit ADC in the controller. A 4-button overlay (120 mm x 30 mm) is applied over the lower portion of the touch screen to provide the ‘UP’, ‘DOWN’, ‘ESC’ and ‘ENTER’ buttons used for navigation and command entry. Each button is 26 mm x 20 mm. The upper portion of the screen thus remains available for use. A single chip touch screen controller (TSC2200 by Texas Instruments). interfaces directly to the four-wire touch screen and uses the SPI bus to communicate with the processor, This controller includes advanced features that enable power saving and simplify coding.

3.1.3 Optional Additional Memory

Provision has been made in the HPMM main unit for the use of an external memory chip. The chip will be a 256 KB (32K x 8) static RAM in a 28 – pin surface mount package. An example candidate is the M48Z35AV from ST microelectronics. The processor can access this SRAM IC through the External Memory Interface (EMIF) which will be enabled on the lower four ports (P4-P7) using the digital crossbar (see Table 3.1). It is proposed that due to the availability of the large number of I/O pins, no address-data multiplexing will be required and so the device will be used in non-multiplexed mode. This external memory will work as an extra data memory for data intensive applications. Currently, code memory is also used to store digitized samples in cases where the number of samples is very large, such as in the steadiness test (see below).

3.1.4 Programming and Updating HPMM Program Code

There exist two options for programming or updating HPMM code. The first involves circuitry that can connect the HPMM via the JTAG interface header to a serial to JTAG adapter. The serial-to-JTAG adapter is connected to the Host PC via the serial port. A proprietary integrated development environment (IDE) running on the host PC then allows code to be compiled, linked and downloaded onto the HPMM via this serial-to-JTAG adapter. This approach is good for initial programming and testing, but since both the adapter and the IDE are necessary, field programming is not feasible in this fashion.

For field programming, a simpler approach is adopted. A firmware updater has been developed and initially downloaded into the HPMM microcontroller flash memory using the JTAG approach. Subsequently, a direct connection between the HPMM and the host PC via the included HPMM serial port is used to download the HPMM code in Intel HEX file format. Simple custom software running on the host will manage handshaking and control of this process.

3.1.5. Main Unit Sensor and Stimulus Generator Subsystems

The main HPMM unit integrates several sensor and stimulus generator subsystems. They include the touch sensor subsystem, the force sensor subsystem, and the LED-based visual stimulus generator subsystem. The following discussion describes each of these in detail.

Touch sensor Subsystem

The touch sensor subsystem consists of thirteen touch sensor regions that are driven by five high-speed capacitive touch sensor integrated circuits. Of these, one is a QT310, while the rest are QT320 chips from Quantum Research Group. An illustration of the touch sensor array is provided in Figure 3.7 under the software section. The touch sensor regions can be divided into four groups, namely the HOME sensor, the LEFT group, the RIGHT group and the extreme group. The HOME sensor is a single region driven by the QT310 touch sensor IC. The QT310, a single channel touch sensor, has been chosen for the HOME electrode because of its faster response time (as fast as 1 ms as opposed to the QT320 which has a best response time of 5ms). This ensures accuracy comparable to lab-based instruments for response speed tests. The remaining regions are driven by QT320 ICs which are dual channel sensors. Thus, one QT320 can drive two regions. The LEFT and RIGHT sensor regions are divided into target and error regions, and the error regions themselves are divided into lateral and fore-aft regions. This division represents an improvement over previous designs of the touch sensor subsystem. The software section of this chapter discusses the use of these sensor groups in specific generic test algorithms. The extreme sensor regions are the two small regions located at the left and right bottom corners on the touch sensor board. They were incorporated in the design to be used as “keys” on the backside of the HPMM main unit, facilitating additional options in the design of the user interface during various operational scenarios. They are not currently used, but Chapter 5 discusses possible uses for them.

Touch Sensor Performance Requirements

The HPMM version 4.0 touch sensor subsystem will be utilized for conducting performance capacity tests such as visual response speed, finger tapping performance, and upper extremity coordination. These applications and others that are currently being researched upon require the touch sensors satisfy certain performance characteristics. These can be stated as follows:

- The ability to detect a touch of a human finger and to function as an on/off switch in response to this touch.
- Fast response time, preferably less than 1 ms.
- Automatic calibration capability.
- Good immunity to electromagnetic interference and cross-talk in a multi-sensor arrangement.
- The ability to work effectively even with small-footprint sense electrodes.

Touch Sensor Parameters

The QT310 touch sensor IC is a charge transfer based capacitive touch sensor IC. It employs bursts of charge transfer cycles to acquire its signal. The capacitor C_s which is connected between the two SENSE pins is a sampling capacitor that forms a floating store of accumulated charge which is switched between the SENSE pins. The electrode which is connected to one of the sense pins is thus used to periodically project a 'sense' field, and hence the capacitance associated with the electrode will increase when a finger is brought close to it. This increase in capacitance C_x will cause charge to be transferred more rapidly into the sampling capacitor C_s. This charge is then amplified by a charge amplifier which drives the input of a single slope switched capacitor ADC. Additional signal processing is also implemented within the sensor IC to reject impulse noise.

To allow large values of C_x, it is necessary to use a large C_s. This increases the available resolution as well as the gain by decreasing the rise of differential voltage across C_s. Longer burst lengths also increase gain and sensitivity, but consume more power. The following is a description of the various programmable parameters of the QT310 /QT320. The QT320 is a two-channel version of the QT310. It has a slower response time than the QT310, which however is sufficient for its applications in the finger tapping performance test and upper extremity coordination test. In fact, the touch sensor subsystem consists of four QT320 sensors and only one QT310 which drives the HOME electrode that is used in tests such as visual response speed, where a higher sensor response speed is desired.

1) Sleep Cycles (SC)

SC is the number of intervals T_{sc} separating two consecutive bursts. This influences the burst spacing parameter T_{bs}:

$$T_{bs} = T_{bd} + (SC \times T_{sc}) \qquad \text{if } SC > 0$$

or

$$T_{bs} = T_{bd} + 2.25 \text{ ms} \qquad \text{if } SC = 0$$

The parameter T_{bd} is the burst duration and is a function of the number of pulses in a burst, which again is a function of C_s and C_x, as mentioned in the previous section. A large value of SC decreases power consumption but will result in a slower response. For this reason, the present version of the HPMM will use a low value for SC.

2) Drift Compensation

Signal drift occurs with changes in C_x, C_s and V_{dd}, electrode contaminations and aging effects. Compensation is achieved by causing the signal reference level to track the raw signal while no detection is in effect. This change should be slow and device slew-rate limited. Positive drift compensation PDC (0-255) should be set to a large number to compensate for the slow increase in C_x (as an object comes close to the electrode). Setting it too fast will cause compensation to occur even before the touch. But NDC (0-255) must be set to a smaller value to compensate quickly for the removal of touch or an object, or after a MOD recalibration (discussed later). This situation applies to the HPMM in tests such as the finger tapping performance and upper extremity coordination where the output od the sensor must not be active until the finger actually touches the electrode, and the reference level must quickly be reached by the internal signal once the finger is removed.

3) Threshold (THR, 0-255)

Threshold is measured in counts of signal deviation from the reference level. If the signal equals or exceeds the threshold value, detection can occur. The detection will end only when the signal goes below the hysteresis level or upon a MOD recalibration. In the context of the HPMM, a low threshold is required because it translates to high sensitivity.

4) Hysteresis (HYS, 0-255)

Hysteresis is measured in terms of counts of signal deviation relative to the threshold level. The output becomes inactive when the C_x level falls below the level corresponding to THR-SYS. A zero value represents no hysteresis, but HYS should not be set greater than THR; this may cause a malfunction. For best results, it must be set between 10% and 40% of the threshold value. Hysterisis affects detection stability. An optimal value of hysterisis is required for the signal to remain stable during detection. If hysterisis is set too low, even very small changes in the detected signal will cause the output to switch, which is not desirable, especially in case of the finger tapping performance test where measures such as the tap duration and duty cycle are vital to the assessment of the performance resource.

5) Detect Integrators

Detect integrators serve to filter out sporadic electrical noise. The detection integrator DIA is a counter that increments as soon as the signal crosses the threshold level, until it reaches the terminal count DIAT (1-255), when the OUT signal is activated. DIB is the end-of-detection counter which counts up as soon as the signal falls below the hysteresis level and the OUT signal is deactivated when DIBT(1-255) is reached. The HPMM touch sensor settings will include a higher count for the detect integrator than for the end of detect integrator. This will ensure that the start of detection is not caused by sporadic noise or an inadvertent touch or brush by the examiner, which is necessary in all touch sensor based performance capacity tests. A low setting for the end of detect integrator will allow a fast response during tests such as simple response speed where it is vital that there be no detection delay after the subject has removed their finger from the sensor.

Detection delays can be long with large burst spacing, so the burst rate can be increased when the DIA or DIB counters are operating. The bits DISA and DISB respectively enable this fast detection, and the normal burst rate resumes after the DIB counter stops counting at the end of detection.

6) Max On Duration (MOD)

MOD (0-255) allows for automatic recalibration if the activation last longer than the designated timeout, T_{mod}. This can be caused by a stray object inadvertently coming in close proximity with the sense electrode. If SC > 0, the delay T_{mod} is

$$T_{mod} = (MOD+1) \times 16 \times T_{bs}$$

If SC = 0, the delay is a function of the burst duration T_{bd}

$$T_{mod} = (MOD+1) \times 256 \times T_{bd}$$

The MOD function is disabled by setting MOD = 255, so that the sensor recalibrates only when part is powered down and started up again. This is suitable in case of the HPMM. Primarily, it is preferable that the output deactivate only when the finger is removed from the touch sensor. This becomes an important issue when dealing with pathologic subjects who may have very slow responses to visual stimuli. Also, given the procedures of conduction of the various tests, one may safely assume that the examiner will not allow any ‘stray object’ to present itself in close proximity to the touch sensors.

7) Polarity (OUTP)

The polarity of the output can be set to active high but is active low by default. The main advantage of the choice of an active low output polarity is that it complements the use of pull up resistors at the sensor outputs. The current drain at the output only occurs when detection occurs, so that the power consumption is much lower. In the active high case, where the output would have to be pulled down during all such times when there was no detection, much higher current drain can be expected.

8) Toggle Mode (TOG)

This mode gives the output a touch-on, touch-off flip flop action, and hence the output *changes* state on detection.

9) Toggle Latch Mode (TOGL)

OUT becomes active on a detection but will become inactive only when a logic low pulse is applied on the /CAL_CLR pin.

10) Heartbeat Output (HB)

Heartbeat indicator pulses are superimposed on the output to indicate the 'health' of the IC. They can be removed by using a capacitor at the output pin or if SC = 0, by setting HB=1. Since the process of touch detection in the HPMM is not a continuous one, the touch sensors are not enabled at all times. Therefore, there is no necessity for constant touch sensor health monitoring, so that the heartbeat signal will be programmatically disabled.

11) Sense direction (POS / NEG)

For positive sense direction (POS), the sensor is calibrated when no object is present and the OUT signal becomes active when object approaches the sensor. For the negative sense direction, the part is calibrated with the object present, and the OUT signal becomes active in the object moves away from the sensor. No extensive analysis is required to show that positive detection is ideal for the HPMM context.

12) Detection Mode (BG or OBJ)

BG (background mode) causes the calibration to occur at the baseline level as opposed to the signal level when the object is present. The detection is made relative to this baseline reference level. In OBJ mode, the reference level becomes the signal level when the object is present. Once again, one can easily see that it is definitely more appropriate to use the BG mode in the HPMM context, because the finger is more often away from the touch sensor than near or upon it.

The following tables provide the parameter settings for the QT310 and QT320 touch sensors in the present HPMM touch sensor subsystem. The QT310 table also provides notes which summarize the reasons behind the choice of the settings, and the same reasons also apply for the QT320 settings.

Table 3.2 QT310 Parameter Settings.

Description	**Symbol**	**Value**	**Notes**
Threshold	THR	6	Low for increased sensitivity.
Hysteresis	HYS	3	50% of the threshold: ensures stable detection
Detection Integrator	DISA	10	Higher count for ensuring valid detection.
End Detection Integrator	DISB	1	Lower count for fast end of detection response.
Negative Drift Compensation	NDC	2	Quicker compensation for removal of finger.
Positive Drift Compensation	PDC	100	Slower compensation to ensure no false detections.
Max-on Duration	MOD	255	Infinite; required for long touch durations.
Burst Length T_{bd} (ms)	BL	1	Results in fast response time for HOME sensor.
Sleep Cycles	SC	0	Also results in faster response time.
Output Polarity	OUTP	0	Active low; ensures low power consumption
Heartbeat Disable	HB	1	Disabled; unnecessary for HPMM context
BG Mode	BG	0	Suitable because finger is more absent than present on the sensor.

Table 3.3 QT320 Parameter Settings.

Channel 1 Specific		
Description	**Symbol**	**Value**
Threshold (cycles)	THR1	6
Hysteresis (cycles)	HYS1	1
Integrator (bursts)	DIAT1	10
Max-On Duration	MOD1	14
Output Mode	OUT1	0
Channel 2 Specific		
Description	**Symbol**	**Value**
Threshold (cycles)	THR2	6
Hysteresis (cycles)	HYS2	1
Integrator (bursts)	DIAT2	10
Max-On Duration	MOD2	14
Output Mode	OUT2	0
Common to Both Channels		
Detection Integrator Speed	DIS	1
Negative Drift Compensation	NDC	2
Positive Drift Compensation	PDC	100
Burst Length T_{bs} (ms)	BL	5
Sleep Cycles	SC	1

Force sensor subsystem

The force sensor subsystem for the HPMM consists of a low-profile top-hat model load cell (LFH-71 from Honeywell, 250 lb maximum load rating). The load cell is a sub-miniature force transducer that utilizes foil strain gages to measure compression loads. Thus the sensor circuit is primarily composed of strain gages in a bridge configuration followed by a fixed gain instrumentation amplifier. The static sensitivity of the overall system is 25mV/lb or 5.618 mV/N, which provides a measurement range of 0 to 889 N and a corresponding output voltage range of 0.25V to 2.4V The sensor is calibrated to include a 0.25V offset (with zero force applied) so that small drifts keep the signal in an operable range.

The subsystem is packaged into the HPMM handle. This allows for greater portability of the overall system because there is no separate cable or grip assembly as in the earlier versions of the HPMM. The output of the force sensor is connected to an analog input channel associated with one of the two ADCs in the HPMM microcontroller ("ADC0") As mentioned previously, this is an ADC which can sample at up to 100 KHz and which works in 12 bit mode. There is an internal programmable gain amplifier feature (gain options of 0.5, 1, 2, 4, 8 and 16) which is set to unity for the force sensing subsystem.. This ADC uses an internally generated reference voltage of 2.4 V and therefore the output of the sensor subsystem is constrained to remain within 2.4 V but appropriate choice of its static sensitivity. The power to the force sensor subsystem (+5V) is provided by the power subsystem on board the HPMM through a separate connection.

Visual Stimulus Generator

To generate the visual stimuli that are required for different performance capacity tests such as simple visual response speed, the HPMM is equipped with two high intensity light emitting diodes (LEDs) on the underside of the main unit. They are capable of emitting red, diffused light of intensity greater than 2000 mcd and are connected to the HPMM microcontroller through an LED driver circuit that consists of two independent power MOSFET switches (IRFD9110 of International Rectifier), one for each LED. These LEDs can be independently controlled because each MOSFET is connected to a separate port pin on the HPMM microcontroller (RIGHT – port 2 pin 7 and LEFT – port 3 pin 5) and the corresponding port registers are bit addressable. Thus, by simply driving the port pin high or low, these LEDs can be turned off or on as required.

3.1.6 Remote Sensor Module-1 (RSM-1)

As indicated previously, the HPMM is equipped with a general interface to support a Remote Sensor Module (RSM). This interface includes several signals including +5V power and ground, connections to five digital port pins, and a connection to an analog input channel on the microcontroller. The definition of the digital port pins will be application specific. Currently, one RSM module has been defined and it is denoted RSM-1 It consists of three subsystems: acceleration measurement, angular rate measurement and speech processing. These are all integrated into one small housing that measures 49mm X 34mm X 19mm and weighs 32g. It is connected to the HPMM main board through an eight wire flexible cable and an 8-pin MiniDIN connector.RSM-1 contains an 11 channel, 12-bit, 200 Ksps ADC (TLV2553 By Texas Instruments) for digitizing various signal conditioned outputs from sensor channels.. Thus, digital data is passed to the main unit from RSM-1 for superior noise performance. An input to the ADC on the main processor of the main unit is incorporated into the RSM interface. This is used on RSM-1 for direct, high speed digitization of the signal conditioned raw speech channel.

Acceleration measurement subsystem

The design of the acceleration measurement subsystem is driven primarily by the desire to accurately measure the oscillatory movements produced in a subject's body part such as the hand-arm combination. However, other possible future applications were also considered and this has impacted the final design utilized.. The present design includes an ADXL210 dual axis accelerometer with a sensitivity of 100mV/g and a specified input range of 0 to 10g. The outputs of this accelerometer are of two kinds; duty cycle modulated digital outputs, and analog outputs. Only the analog outputs are used in the design. For steadiness/tremor measurement, these outputs (one for each axis) are first filtered with simple high-pass and low-pass filters to restrict their frequency content to lie between 1 Hz and 22 Hz and then amplified by a gain of 11. However, for each axis, the unamplified raw output signal that includes the dc component is also retained and connected to separate channels of the RSM-1 ADC. These signals can be useful for other performance tests and also for extending the effective measurement range for very large and high frequency abnormal motions. Both the conditioned and raw outputs are thus available for digitization using the ADC. The accelerometer chip is mounted perpendicularly to the main RSM printed circuit board; i.e., along the y – axis shown in figure 3.2 below, to measure accelerations along the x and y axes.

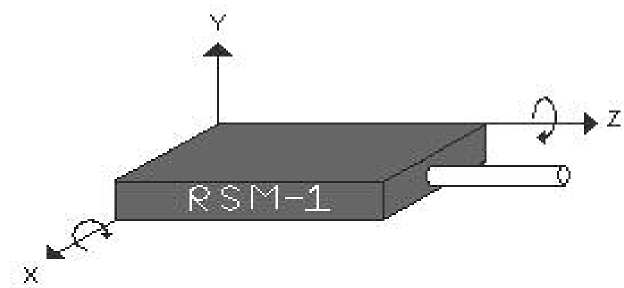

Figure 3.2 The Remote Sensor Module 1 (RSM-1).

The overall system sensitivity for the A.C.-coupled channels is:

Sensitivity = Accelerometer Sensitivity x Amplifier Gain x ADC Conversion Factor

= 100 mV/g x 11 x 4096 ADU / 5V

= 901.12 ADU/g.

where ADU = Analog-to-Digital converter units. For the 12 bit A/D used, the measurement range is thus 0 g to 4.5 g. The overall sensitivity for the D.C.-coupled channels is 81.92 ADU/g. This provides a theoretical measurement range of 0 – 50 g which is more than the sensor's output range (0 – 10 g). Thus, the effective range is 0 – 10 g.

Angular Rate Measurement Subsystem

This subsystem consists of two integrated circuit MEMS based angular rate sensors (ENC05-EA of Murata). The basis for the operation of these sensors is the Coriolis Effect. An out of plane, bending force called the Coriolis force is caused by the momentum stored in a vibrating element when a rotation is applied to it. The sensor demodulates this force and accurately depicts the rotational rate.

Each sensor measures the angular rate along one axis and sensors are mounted so as to be able to sense angular rates about two orthogonal axes. For example, in case of the steadiness test, one sensor measures the rate of flexion extension of the wrist (which is about the x-axis shown in figure 3.2) while the other measures the rate of pronation-supination of the forearm (which is about the y-axis shown in figure 3.2). The nominal static sensitivity of these sensors is 1.11 mV/deg/s (before signal conditioning) and they have been found to produce fairly linear outputs for inputs up to 1000 deg/s. This brings to light the flexibility in the possible applications of these sensors. While in the steadiness testing they are used to measure rates of a few deg/s, they can also be harnessed to measure quantities such as the rotation speed of the human arm about the shoulder joint, which is of the order of hundreds of deg/s.

The outputs of the angular rate sensors are filtered to remove the dc components and then amplified by a factor of 11. Again, the raw outputs are also retained and both raw and conditioned outputs are digitized using two additional channels of the RSM-1 ADC. For the angular rate measurement subsystem, the overall system sensitivity for the A.C. coupled channel is computed as follows:

Sensitivity = Angular Rate Sensor Sensitivity x Gain x ADC Conversion factor

= 1.11 mV/deg/s x 11 x 4096 ADU / 5V

= 10 ADU/deg/s.

Thus, with the use of a 12-bit ADC, the measurement range for the A.C. coupled channel is 0 - 409.6 deg/s. For the D.C. coupled channel, the overall sensitivity is 0.909 ADU/deg/s which gives a theoretical measurement range of 0 - 4,506 deg/s.

Speech Measurement Subsystem

The RSM-1 unit also contains a microphone and preamplifier for future use in a series of performance capacity tests that involve speech. The output of the speech circuitry on the RSM which is in the form of a 'raw speech' signal is connected the analog input channel 1 on the HPMM microcontroller. Thus, this raw speech signal can be sampled by the ADC0 system that was described earlier. This subsystem is not presently used for any tests and therefore is not detailed in this thesis. Specifications (e.g., gain and frequency response) have not been finalized.

RSM System Interconnections

The arrangement of the functional blocks in the RSM and their interconnections is as shown in figure 3.3. Although the filters and amplifiers are shown as dual-channel blocks for clarity, there are in fact one amplifier and one filter per channel and are implemented using operational amplifiers. The ADC communicates with the HPMM microcontroller through the Serial Peripheral Interface (SPI). This is a four wire interface that enables efficient full duplex serial communication in a master slave configuration. The SPI interface is enabled on port 0 of the HPMM microcontroller, after proper configuration of the microcontroller's digital crossbar. Power to the RSM (5V) is supplied via a separate LDO on the main HPMM board.

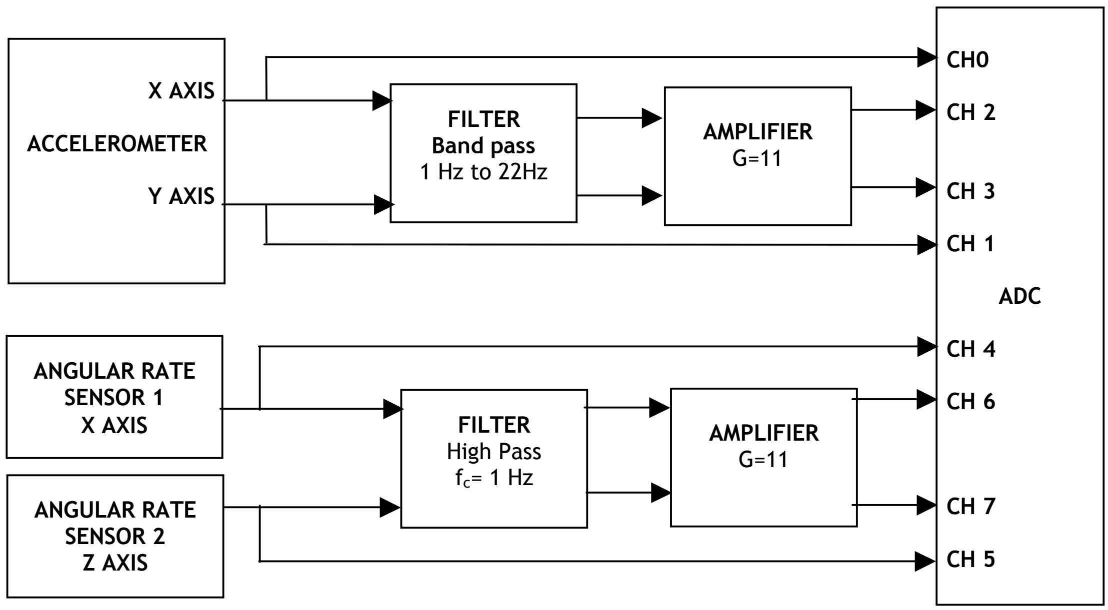

Figure 3.3 Conceptual Block diagram for Acceleration and Angular Rate Subsystems.

3.1.7 Power Management

The power management subsystem of the HPMM consists of two dc/dc converters and five low-dropout regulators (LDOs) all of which are housed on the HPMM main board. The dc-dc converters (LT1300 of Linear Technology) convert the 3.6V input voltage from the battery to 3.3V for the processor and touch screen controller, and 5 V for the remaining subsystems respectively. The second (5V) dc-dc converter has its active low V_{SHDN} pin connected to a port pin on the microcontroller, so that the entire 5V subsystem set can be disabled with a single instruction. This is especially useful when the HPMM needs to be placed in power-saving or sleep mode.

The five low dropout regulators (REG101 of Texas Instruments) all draw power from the second LT1300 described above. They control power to the LCD, the RSM, the touch screen, the serial communication subsystem and the accessories such as the LEDs and the beeper. Each of these has an enable pin which is active high logic. The enable pins are connected to unique port pins on the microcontroller. Thus, power to each subsystem can be individually enabled or disabled when needed by using software instructions for power management.

Bench measurements were made with a digital multimeter to determine the power consumption impact, from the perspective of the rechargeable battery, for each of the major HPMM subsystems (Table 3.4). At the input to the power supply subsystems (i.e., the point at which the battery would be attached), the multimeter was inserted in series with the positive supply lead to an adjustable voltage bench power supply set for an output of 3.4V. Current was measured with all subsystems disabled (i.e., only the microcontroller and basic support subsystems powered) and then with each subsystem enabled (one at a time). The change in current over the microcontroller baseline was computed for each subsystem. This is multiplied by 3.4V to determine the impact on power consumption at the battery.

Table 3.4 Contribution of Various Subsystems to Power Consumption at Source.

Subsystem	Change in Current (mA)	Contribution to Power Consumption (mW)
Remote Sensor Module	32.9	111.86
Touch Sensor Subsystem	22.9	77.86
Serial Communications Subsystem	0.1	0.34
LCD Subsystem	59.4	201.96
Microcontroller and support	60.6	206.04
Total Power Consumption Contribution		598.06

The table shows that the total power consumed in a condition where all subsystems are enabled is 598.06 mW. Given that the proposed power source for the HPMM is a battery pack that provides 1600 mAh at 3.6 V, the power rating of the battery pack is 5760 mWh. This allows the HPMM to run in the 'all systems running' condition for over 9.5 hours. Considering that there is never a situation when all subsystems are simultaneously running, it is very likely that an 8 hour minimum operational time between charges can be achieved.

3.2 Software Implementation

3.2.1 Operating System

The HPMM operating system is intended to provide a basic set of functions that supports its operation. These include: user interface management (menu generation and display, monitoring of user inputs and port status), calibration of sensors (where applicable), power management and other yet to be implemented maintenance functions.

User Interface Management

Two separate sections of subroutines called the LCD Module and the Touch Screen Module contain all routines required to manage these components. The touch screen routines implement functionality such as using the SPI communications to initialize the touch controller, acquire data from the touch screen controller, scan for touch, and map the coordinates of the touched region to the four button overlay (esc, enter, up and down). The LCD Module consists of routines that initialize the T6963C LCD controller, and subroutines that build pages for each individual screen that is displayed to the user, going from the menu screens to the test result pages. The communication between the processor and LCD involves sending a set of specific code words that are organized as command and data sets; each command is followed by some data specific to that command. The initialization consists of sending command-data sets for specifications like text home address, text area, graphics home address, graphics area, mode setting, address pointer setting, etc. Relevant reference information to support programming is supplied in the T6963C data sheet from Toshiba. This LCD subsystem is a 5 V subsystem and the PWRE_LCD bit in port 1 must be set in order to enable the REG101 LDO which provides power to the LCD controller. The POWER5V bit must also be cleared to enable the LT1300 regulator thatprovides power to all 5V subsystems.

A major component of the user interface are a series of hierarchical menus that permit selection of mode (e.g., Generic Test Mode, Protocol Driven Mode, Maintenance

Mode, etc.), and subsequently, options associated with each mode. Menu generation and selection management are coded as the MENUCTRL and ROUTECTRL subroutines, respectively. Only options associated with calibration and the Generic Test Mode are implemented at present.

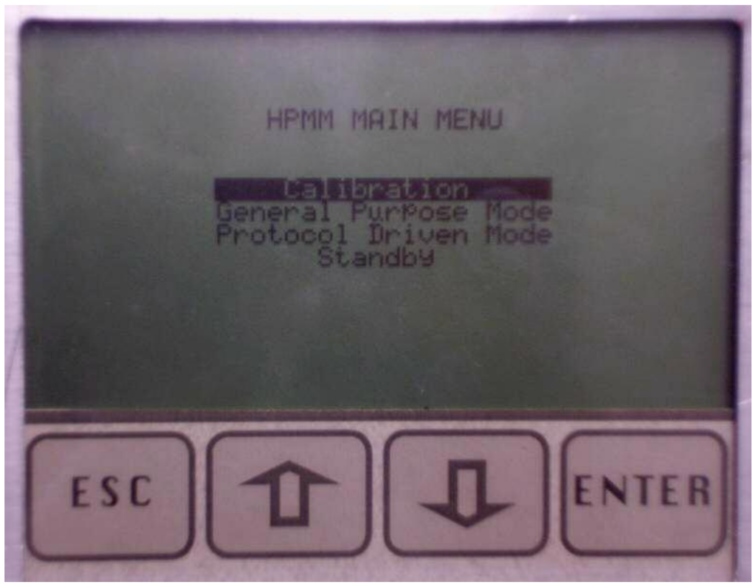

Figure 3.4 The HPMM Main Menu

In the Generic Test Mode, the five generic tests that are currently implemented can be selected. Regardless of the test selected, the operating system manages a common sequence of events. Upon selection of a particular test, the corresponding GTA routine is called which further call their own subroutines as required for the execution of the selected test. Prior to actual execution of a test, the HPMM produces a screen with a prompt asking the operator to "proceed when ready" (allowing the subject to be readied for a test) by pressing "enter". When the selected test is completed, results are displayed and the user is prompted to repeat the test or to return to the main menu.

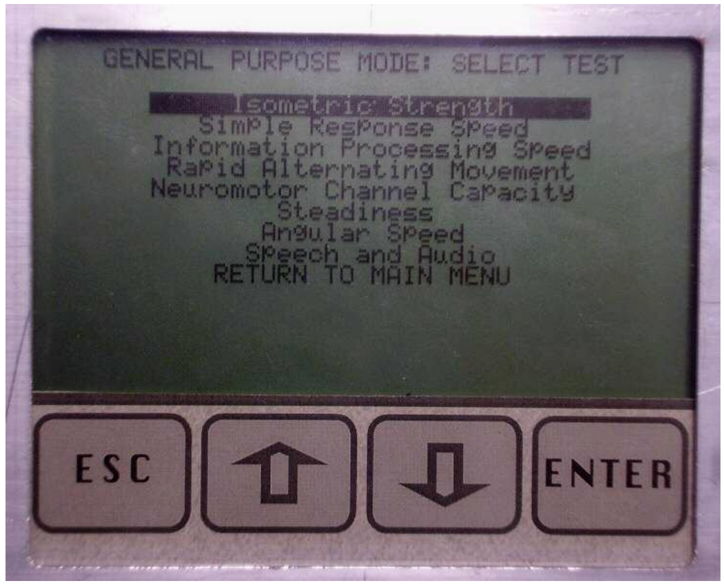

Figure 3.5 The Generic Test Mode Menu

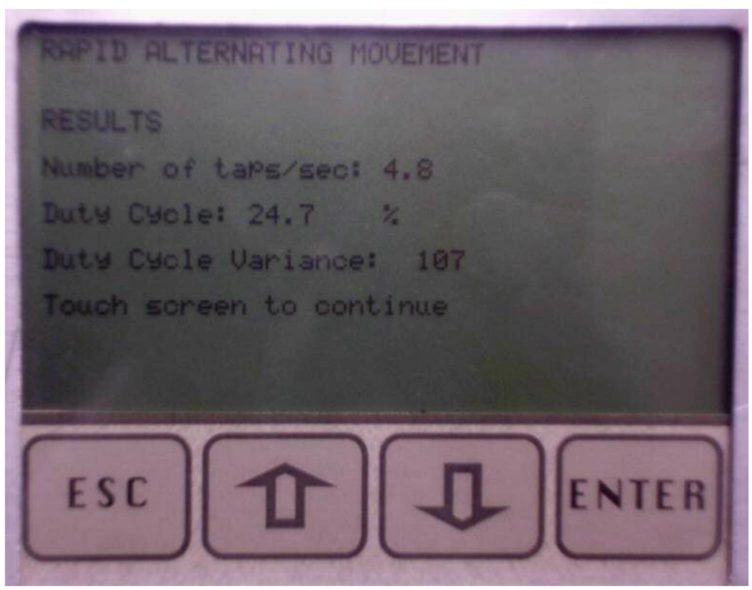

Fig 3.6 Example Result Screen

A set of lower level subroutines were also developed for use by various generic test algorithms (GTAs) as need. These are contained in the "Utility Routines" section of the code and include mathematical algorithms such as 24 bit division, as well as simple hardware management routines such as the BEEP routine which runs the piezoelectric beeper.

HPMM Resource Sharing

The control of HPMM resources is switched between the OS routines and the GTA routines as the device is taken through a test session. Upon startup, the OS has control of the HPMM and this remains the case until the test administrator selects "READY" after choosing a particular generic test algorithm from the Generic Test Mode Menu. At this time, control is transferred to the GTA routines until the test is run completely and all results have been compiled. Control is then regained by the OS routines which will run the user interface subroutines to display results. Even in the case of repetition of a test, the resources are intermittently returned to the OS routines and then transferred back to the GTA for repetition. This mechanism provides a clear resource allocation protocol and avoids resource conflicts at any given time.

Calibration

This function involves calibration of sensors such as the accelerometer, rotational rate sensors and the force sensor. Calibration is performed once at startup, and all three sensor subsystems are calibrated only for offset, not for gain (sensitivity). The resulting sensor offsets are stored in system ROM for later use during the algorithm execution. While the calibration procedure is executed, no user inputs from the touch screen are accepted. The calibration lasts for approximately 5 seconds. The sensor subsystems that are being calibrated are individually enabled during this procedure and disabled immediately after. This ensures that no power is wasted and provides for longer battery life. It may be noted that the remote sensor module (RSM) must be plugged in before startup and placed steady on a flat surface in order that the sensors contained therein might be calibrated correctly.

3.2.2 Generic Test Algorithms

A major objective of this thesis is to review, enhance as necessary, implement, and evaluate the same set of generic tests that were implemented in version 3.0 of the HPMM. The software routine that clearly and precisely defines the implementation of a given test is referred to as a generic test algorithm (GTA). The fundamental design and operation of algorithms and the associated test administration procedures have been rigorously analyzed and tested in a previous study (Sriwatanapongse, 2002). These GTAs are largely based on the corresponding tests in the laboratory based Human Performance Capacity Measurement System (Kondraske, 1990). The specifications for algorithm constituting each GTA are described in more detail in an Human Performance Institute technical report (Kondraske, 2002).

Table 3.5 Description of Generic Test Algorithms.

GTA ID	GTA Name	GTA Description
GTA 1	Isometric Strength Test	Measurement of the force production capacity of muscles in an isometric test. Measures the capacity of a muscle or muscle groups to develop tension. Two sub-modes; grip and resistance, and both use the same algorithm.
GTA 2	Simple Visual Response Speed Test	This test measures the speed at which a response to a simple visual stimulus (i.e., low information content) can be generated centrally to produce a simple upper extremity motor action. The focus is on speed, indirectly measured as the time required by the subject to detect the visual stimulus and generate the response command using a selected upper extremity.
GTA 4	Rapid Alternating Movement Test	The Rapid Alternating Movement test measures the capacity for speed of movement in a simple reciprocal motion task. The alternating nature of the task stresses neuromotor coordination resources. This test is sometimes referred to as the 'finger tapping performance' test.
GTA 5	Upper Extremity Neuromotor Channel Capacity Test	The Neuromotor Channel Capacity Test measures the availability of a performance resource that is related to the speed and accuracy of movement, and their tradeoff. It is essentially a measure of coordination.
GTA 6	Steadiness Test	The Steadiness Test is a generic test of the steadiness of a particular body segment. This will most frequently be applied to a subject's hand (or hand/arm combination). In the generic test administration sense, this could also be performed on other body segments (e.g., head or lower extremities).

3.2.3 GTA 1: Isometric Strength Test

A static or isometric strength test is a test to measure the capacity of muscles to produce force in such way that there is no substantial extension of the muscles and no movement occurs. It measures the capacity of muscle groups to develop tension. There are two different sub-modes for testing, grip and resistance, but the same algorithm is employed. The different modes pertain to different procedures in which the force sensor subsystem is employed in its interaction with the subject under test.

Upon selecting the 'Isometric Strength Test' option from the menu, the GTA1START routine is called. The appropriate configuration settings for the power management and data acquisition subsystems are a part of the initialization. The ADC that is on the microcontroller chip (ADC0) is used for this test. A beep signals the beginning of the test. When the subject begins squeezing the grip sensor assembly, the microcontroller constantly monitors the ADC output samples and waits for the applied force to cross a preset threshold (30 N).). Once the threshold is crossed, the microcontroller samples the grip sensor output for a period of 3 seconds. The calibrated sensor offset value is subtracted from each incoming sample, and a variable that stores the sample corresponding to the maximum applied force is continuously updated. After the 3 second period, the processing ceases but sampling continues until the applied force falls below the threshold value. The acquisition is then stopped and the highest applied force is the result of the test. This is then converted from A/D units (henceforth referred to as ADUs) to newtons and reported on the LCD.

The system static sensitivity is calculated as follows:

Force Sensor Sensitivity: 25 mV / lb or 5.618 mV/N

Voltage Divider: 0.5 V / V

ADC: 4096 ADU / 2.4 V = 1706.67 ADU/V

Multiplying these system functions together we obtain an overall system sensitivity of 4.794 ADU/N. The calibration offset is subtracted from each sample as it is acquired and finally the sample corresponding to the maximum exerted force is converted from ADU to force units (Newtons) and reported on the LCD.

3.2.4 GTA 2: Simple Visual Response Speed Test

This test is exactly the same as in version 3; for a more detailed discussion, see (Sriwatanapongse, 2002). The procedure begins with the subject placing the index finger of the dominant side hand on the HOME touch sensor (tips of digits 3 and 4 may also be included). When this touch is detected, it is checked for again after a one second delay. An error is signaled if the finger is not present on the sensor by blinking the LEDs and the test is restarted. This permits discrimination of a true attempt to start a test from an inadvertent touch of the home sensor by the examiner in the process of position the HPMM for this test. If this check is passed, a beep is signaled to start the test. After a random delay of 1 to 3 seconds, both LEDs are turned on simultaneously. A timer is started that will measure the time from the point the LEDs are lit to the point the subject takes the finger off the sensor with a quick motion of the fore-arm. The reciprocal of this ‘response time’ is computed and the result is the response speed with units of responses per second (resp/s). This result is reported on the LCD.

3.2.5 GTA 4: Rapid Alternating Movement Test

The rapid alternating movement test is used to stress selected neuromotor coordination resources to assess how fast a person can reciprocally move about an isolated body joint. A specific manner in which generic test is used is to characterize finger tapping performance, which is used here as a basis to provide a description of this GTA and associated procedures.

The test procedure begins with a single beep. The subject then begins tapping “as fast and consistently as possible” at any one touch sensor group (either left or right). The tapping must be with the index finger only with motion restricted to the metacarpophalangeal joint (knuckle). No wrist or elbow movement is allowed. The acquisition from the touch sensor group does not begin till the finger remains on the sensor(s) for three consecutive 10 ms samples, reflective of the first “true tap”. When this three-sample check is satisfied, the remaining acquired samples (at 10 ms intervals) are stored in external memory. This sampling occurs for a period of 11 seconds. During this period, whenever there is a change in the sensor status, (such as when the finger is placed on or lifted off the sensors) a 3 second timer is started (or restarted). If there is no change in the sensor states before the 3 seconds have elapsed, a “false test start” is detected (i.e., continuous tapping is not taking place) and the test is restarted.

The acquired samples are then analyzed to compute the number of taps, the tap duty cycle for each tap, and then the mean and standard deviation of the tap duty cycles.

Within a single finger tap, if the finger is on the sensor for n samples and off the sensor for z samples, then the duty cycle for that tap is:

$$\text{Tap Duty Cycle} = n / (n + z)$$

This duty cycle value is calculated for each and every tap. For the computation of the results, the following equations are used:

$$\text{Tapping Speed} = \text{Number of Taps} / \text{Total Acquisition Time}$$

$$\text{Tap duty cycle mean} = \text{Sum of Tap Duty Cycles} / \text{Number of tap duty cycles}$$

$$\text{Tap Duty Cycle SD} = \frac{\Sigma[(\text{Tap Duty Cycle})_n - \text{Tap Duty Cycle Mean}]^2}{\text{Number of Tap Duty Cycles}}$$

3.2.6 GTA 5: Upper Extremity Coordination Test

The coordination or neuromotor channel capacity (NMCC) of the upper extremity is measured by this GTA. This performance resource is related to the speed and accuracy of movement, and these two measurements form the secondary measures of the test, while NMCC is the primary measurement. A detailed description of the algorithm is provided in (Sriwatanapongse, 2002). The procedure remains the same for this version of the HPMM. A single beep signals the beginning of the test. The data acquisition is in the same fashion as for the previous GTA (e.g., continuous 10 ms interval samples of all the touch sensors are saved in memory) , and includes the three sample check and the three second timer for eliminating false starts. The subject is advised to alternately touch the left and right target regions which are illustrated below, while trying to be as accurate and as fast as possible. A single beep signals the beginning of the test. The sensors are checked to ensure that the finger is present on any one sensor (left or right) for at least three consecutive samples. When this check is passed, the algorithm begins to sample and store the sensor states at a rate of 100 Hz. Any change in sensor state will cause a 3 second timer to start. Should there be no further change before 3 seconds elapse, the timer will timeout and a 'false-start' will be detected. The test is then restarted. The first sample that shows a change in sensor state determines which sensor was touched, although it may so happen that during the touch, which can last up to 50-60 ms, the finger may also cover another sensor. For example, if the subject touches the error region in the first sample of the touch, but eventually also covers the target region (the finger is on the border of the target-error regions), the result for that touch is still counted as an error.

A double beep signals the end of the test. The equations for the speed and accuracy computations are the same as those presented in (Sriwatanapongse, 2002). One may note that the unit used for speed during the computation of neuromotor channel capacity is cycles/s, although the reported unit is cm/s in the results section. A slight modification has been made for the computation of NMCC. The equation is:

$$\text{NMCC} = \text{Speed} \times \text{Accuracy} \times \log_2(A/W + 1) \quad \text{bits/s}$$

The dimensions of the target width and movement amplitude (target separation) have not been changed in this version of the HPMM, so that the same calculations for index of task difficulty also still apply. The appropriate compromise between speed and accuracy will result in the best value of NMCC.

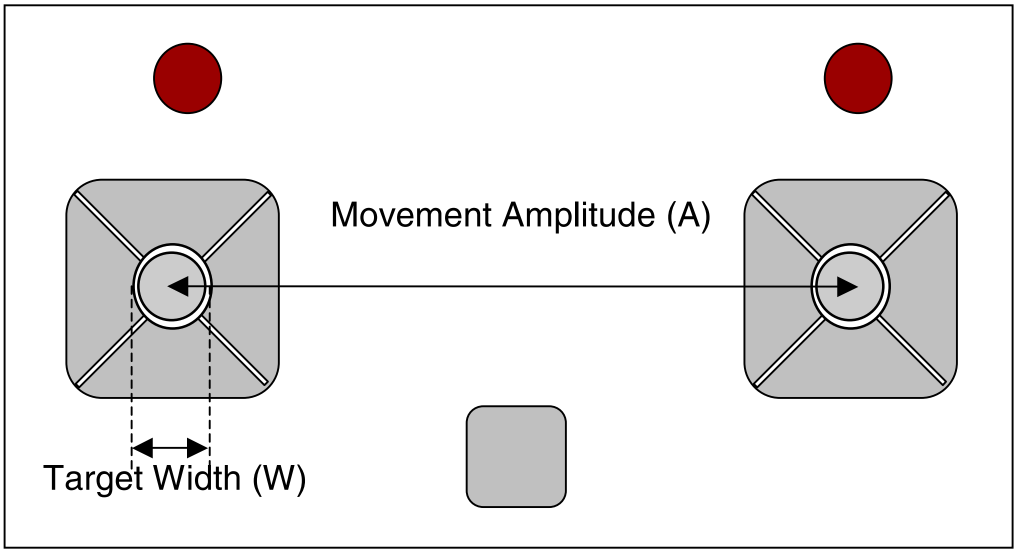

Figure 3.7 Touch Sensor Layout.

The major difference between the touch sensor arrangement for this and the previous HPMM versions is that the error regions in this version are separated into lateral and fore-aft error regions, as illustrated below. This leads to the fact that while making a decision as to whether there was a hit or an error one must take into account the fact that that an error could be one of either lateral or fore-aft nature. This distinction is currently avoided by logically OR-ing the sensor outputs for these two regions. But in the future, the errors will be distinguished in order to compute different lateral and fore-aft accuracies.

3.2.7 GTA 6: Hand-Arm Steadiness Test

The steadiness test has been given special emphasis in this thesis. It has been expanded to include four measures instead of the two used previously by incorporating two angular rate measures in addition to translational accelerations. The primary result in this test is one that has been formulated after application of the General Systems Performance Theory (Kondraske 2000a) and is a single number that represents the composite steadiness or "4 degree of freedom (DOF) steadiness of the body part under test.

Conceptual Background

Steadiness can be measured with respect to any body part that is capable of motion. To understand this generic test, an outstretched hand-arm combination is employed. Of the six degrees of freedom required to completely describe motion, three are translational and three are rotational. The three axes involved in the quantification of the motion along these degrees of freedom can be described as vertical, lateral and longitudinal for the hand-arm combination with reference to a sensing point on the dorsal surface of the hand. The hand-arm combination or any object of interest can thus either translate along or rotate about either of these axes. In the case of the hand-arm combination, we expect negligible translation along the longitudinal axis (forward-backward) and negligible rotation about the vertical axis. We thus restrict ourselves to only four degrees of freedom.

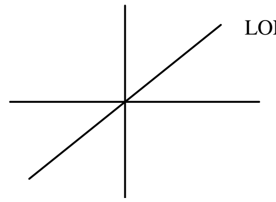

Figure 3.8 Three Axes, Six Degrees of Freedom.

It may be noted also that rotational measurements are new to the HPMM design and have been incorporated beginning this current version. Also, while rotational measurements are rate based (deg/s), translational measurements are acceleration based (m/s^2 or g). And in keeping with the principles of the General Systems Performance Theory, the average values of these quantities are inverted to obtain translational acceleration based "steadiness" and rotational rate based "steadiness", where more steadiness is indicated by a larger numerical value. Finally, these four secondary measures are multiplied together to obtain the single number result called 4-DOF steadiness. Averaging the four results is not a conceptually sound solution because they do not all have the same units and dimensions. This approach also allows the dimensionality of all four quantities to be preserved in the composite score.

Translational Acceleration based Steadiness

The translational motion in the hand is measured in terms of acceleration. We begin with displacement. The motion is modeled as a sinusoidal one that can be described mathematically as:

$$s(t) = A \sin(2\pi ft) \qquad m$$

where A, imeters, is the amplitude of the displacement with frequency f in Hz.

The corresponding acceleration is obtained by differentiating this equation twice:

$$a(t) = 4\pi^2 f^2 A \sin(2\pi ft) \qquad m/s^2$$

Further, the units of acceleration are converted to g's. For example, a displacement of 1 cm (peak) leads to an acceleration of roughly 1g and a displacement of 0.1 mm corresponds to an acceleration of 0.01 g.

While it is difficult to accurately estimate what the values are of the smallest and largest accelerations that can be produced in the human hand, the range described above (i.e., 0.1 to 10 mm) is assumed to be an adequate estimate.. These values were used to determine overall gains and measurement range in the hardware design. Inverting these limits gives 1 1/g and 100 1/g and these are the units ('one by g') that will go into the steadiness measurement model. These numbers decrease with increased acceleration and indicate less steadiness for more motion or acceleration.

Rotational Rate based Steadiness

For obtaining a model for this kind type of steadiness measurement, we begin with the rotation of the hand about an axis. The rotation rate equation is

$$V = \omega r \qquad rad/s$$

It is estimated the range of displacements of interest on the back of the hand due only to angular motion at the wrist or forearm would range from approximately 0.1 mm to

10mm. Given an estimate of the moment arm (r), the size of angle can be estimated. Incorporating an estimate of the frequency associated with the angular motion (f = 5 Hz), an estimate of the range of angular rates can be determined. Table 3.2 lists these estimates for three different radii. The first column represents the radius which in other words is the distance of the rotational rate sensor from the wrist. The second and third columns are mathematically estimated angles and rotation rates. These values were used to determine overall gains and measurement range in the hardware design.

Table 3.6 Estimates of rotational rate based on displacement estimates.

Distance from wrist (mm)	Angle of Rotation (deg)		Rate of Rotation (deg/s)	
	Min	Max	Min	Max
30	0.19	18.43	6.0	600.0
40	0.14	14.04	4.5	450.0
50	0.11	11.31	3.6	360.0

The results of these measurements in deg/s are converted as mentioned earlier to s/deg in order to obtain values of steadiness (for two axes) that is consistent with performance theory.

Measurement Algorithm

Assuming that the calibration routine has been executed, the test administrator straps the RSM to the hand of the subject. The test administrator can select the steadiness test from the GTA menu and commence the test by pressing START. The power subsystem associated with the RSM is activated and a small delay is provided to allow the sensors to stabilize. A single beep signals the test start. The ADC routine is called which samples the four channels coming from the four sensor outputs successively. Thus one set of four samples is obtained every 10ms. While the accelerometer channels' samples are stored in on-chip external memory, the angular rate sensors' samples are stored in code memory. After a period of 10s, the sampling is stopped and analysis begins.

In the analysis section, the accelerometer samples are processed first, one axis after the other. Firstly, the left-justified samples are bitwise shifted to right justify them. For each sample the calibrated sensor offset is subtracted and the absolute value of this difference is computed. Then for each axis, the average of the absolute differences is computed. This average (in ADUs) is then divided into the static sensitivity of the system (901.12 ADU/g) to obtain in units of 1/g the required translational acceleration-based steadiness value. The same procedure is repeated for the rotational rate based steadiness measurement after moving the acquired samples from code memory into on-chip memory. The four results are then converted into BCD format and finally mapped onto the LCD character map for display.

The following flowchart shows the structure of the software written to implement GTA 6. Although the later portion of it (after the acquisition stage) reflects only the path for translational steadiness, the exact same path applies to rotational steadiness except the difference in the calibration offsets and the system static sensitivities.

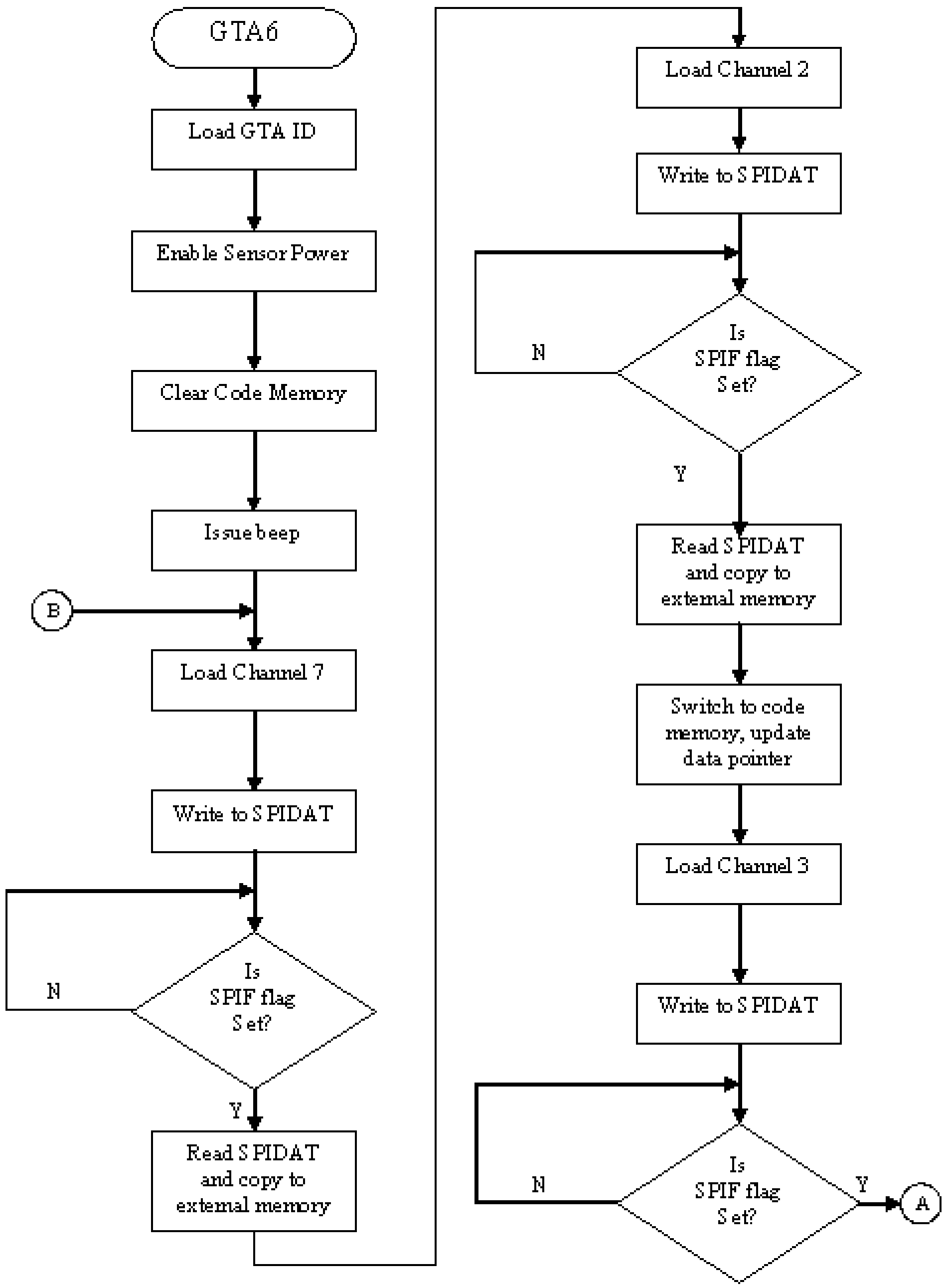

Figure 3.9 Flowchart (part 1) for GTA 6: Hand-Arm Steadiness Test.

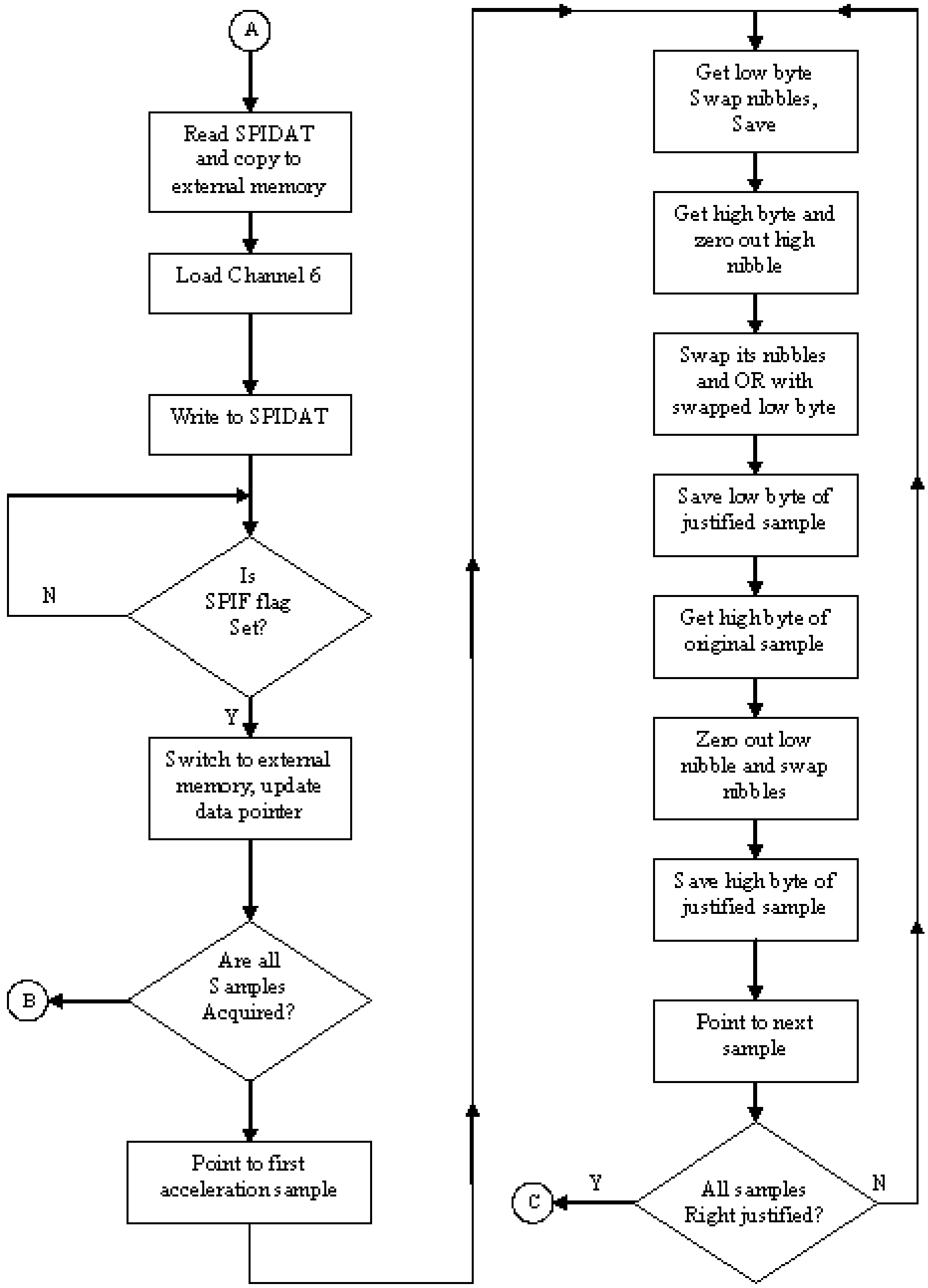

Figure 3.10 Flowchart (part 2) for GTA 6: Hand-Arm Steadiness Test.

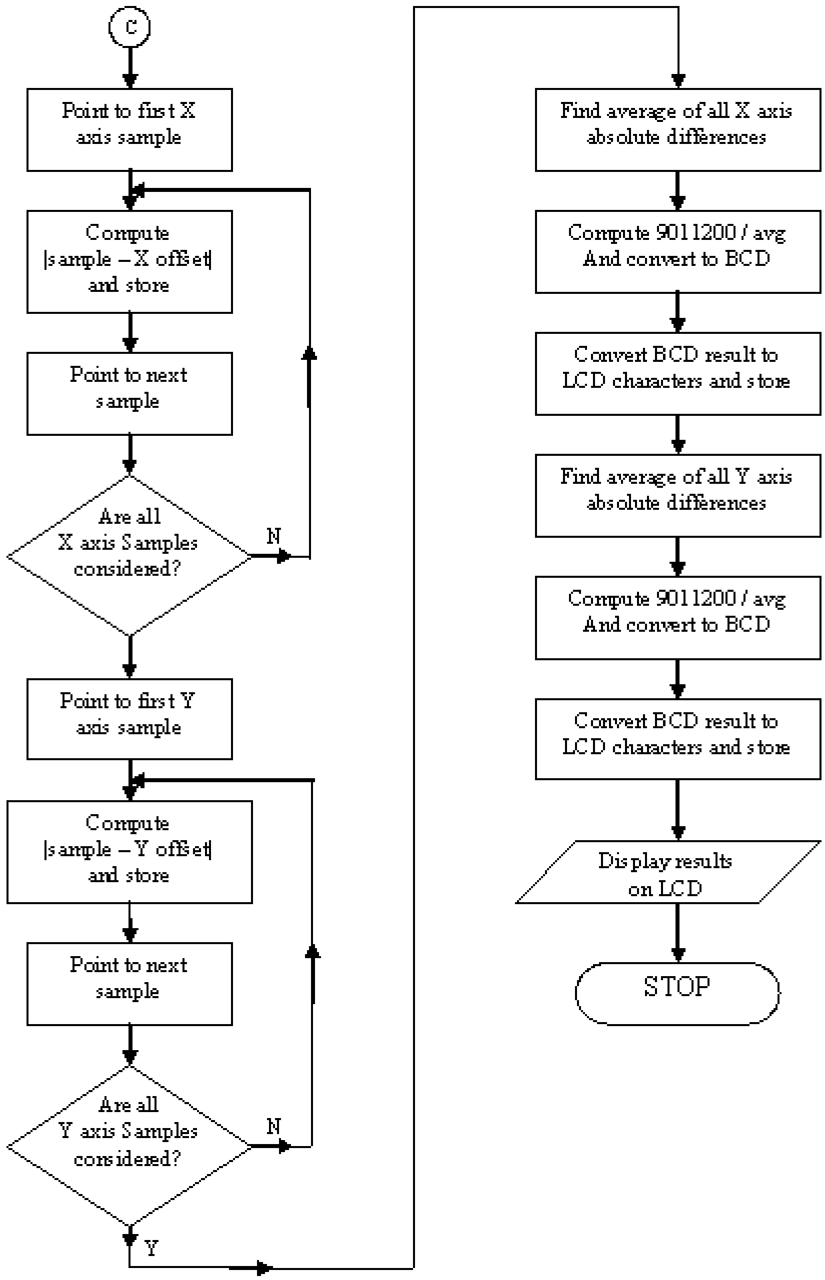

Figure 3.11 Flowchart (part 3) for GTA 6: Hand-Arm Steadiness Test.

3.3 Support Subroutines

The support subroutines are those that are called by every GTA. They include user-interface drivers, communication routines, mathematical subroutines and delay routines. The user interface drivers deal with three components of the user interface namely the touch screen, the LCD and the beeper. The simplest of the three is of course the beeper and there is only one routine that is associated with it. One may take note of the fact the beeper circuit gets its input from the microcontroller DAC, which is currently a square wave. Thus, the business of the beeper routine is to use the DAC to produce this square wave.

The touch screen has an elaborate initialization routine followed by a routine to scan for a touch and routines that convert the coordinates to button numbers (either ESC, ENTER, UP or DOWN). The core routine in the touch screen interface code is the SPI transfer routine that utilizes the SPI communication interface to send commands and obtain data from the TSC2200 touch screen controller.

The LCD subsection has a large set of subroutines. To begin, there are subroutines for building the start screens of each GTA and also the result screens of each GTA. There are also routines that build screens for the menus, i.e. the startup menu and the GTA menu. Further, there are system routines that set the cursor, erase a page, erase a row, set the working page, modify the attribute page, and highlight a row and such other tasks. At even lower levels, there are routines which send a message byte or a command byte to the T6963C LCD controller. There is also a routine to convert from BCD to the LCD character map which is a very useful routine for storing results that will later be read by the LCD controller. This subsection also contains a large set of data variables which are the contents of the menus and messages that go out to the screen.

Another set of routines are the serial communication subroutines. These are used to connect the HPMM via the serial port to the host PC. These routines are used to power-up and enable the serial communication subsystem of the HPMM, convert LCD characters to ASCII, and at the core level to send a byte out of the serial port.

Finally, a set of mathematical subroutines perform 24 bit division, 16 bit by 24 bit multiplications, and conversion from binary to packed BCD. The last set of support subroutines consists of various small, useful delay routines and one very important timer 0 interrupt service routine which is in fact located at 000BH in code memory.

3.4 Memory Utilization Plan

As mentioned earlier, the HPMM microcontroller has 64 KB of code memory and 4KB of on-chip external memory. These resources have been utilized to store the HPMM software code and data elements, and an organizational description is best provided by a memory map. The following table shows the memory map for the current version of the HPMM software.

Table 3.7 Software Memory Map.

Code Memory (Non-Volatile)		
Start Address	**End Address**	**Contents**
(hex)	**(hex)**	
000B	000B	Timer 0 interrupt vector
0100	03E2	Operating System Routines
03E3	05CF	Calibration routines
05D0	0751	GTA 1 Code
0752	086B	GTA 2 Code
086C	0B97	GTA 4 Code
0B98	0DE9	GTA 5 Code
0DEA	11FD	GTA 6 Code
11FE	2151	LCD Routines
2152	229E	Touch Screen Routines
229F	2526	Mathematical and Timer Routines
3000	3FA0	Angular rate sensors samples from GTA 6
External (On-Chip) Memory (Volatile)		
0000	0258	Grip Sensor samples from GTA 1
0B00	0F05	Tap / Touch samples from GTA 4 and GTA 5
0000	0FA0	Accelerometer samples from GTA 6
0F30	0FE6	Test results buffer read by LCD code

CHAPTER 4

EXPERIMENTAL EVALUATION

4.1. Overview and Objectives

Reported in this chapter are the results of experiments conducted to investigate the performance of the current HPMM prototype. To investigate the reliability of the set of measures implemented, a test-retest repeated measures design with two sessions was used. This protocol also provides data that is useful for gaining insight into validity of measures. The methods are similar to those incorporated in studies of earlier laboratory based instruments and earlier versions of the HPMM.

4.2 Methods

Twenty normal adults volunteered for the study.. The set consisted of 10 males and 10 females. The males averaged 25.1 years in age and the females averaged 24.4 years, with the age ranges being 23 – 26 years for females and 23-28 years for males. Subjects were recruited from the staff and student community at the University of Texas at Arlington. The study was reviewed and approved by the UT Arlington Institutional Review Board. A signed informed consent document was obtained from each subject.

Subjects were tested in two sessions on the same day separated by a 10 minute break. A given "test" consisted of a predetermined number of trials for each of the five GTAs. Final results were determined using rules employed in earlier laboratory based instruments and earlier versions of the HPMM. Detailed test administration procedures are provided in Appendix A. The pictures below summarize the set-up of the HPMM relative to the test subject for each of the tests evaluated.

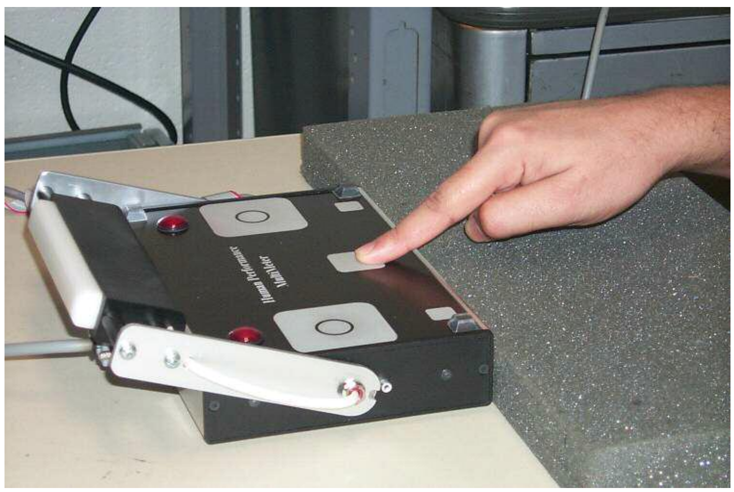

Figure 4.1 Finger Position Before LEDs Turn On in Visual Response Speed Test.

Figure 4.2 HPMM Position for the Grip Strength Test.

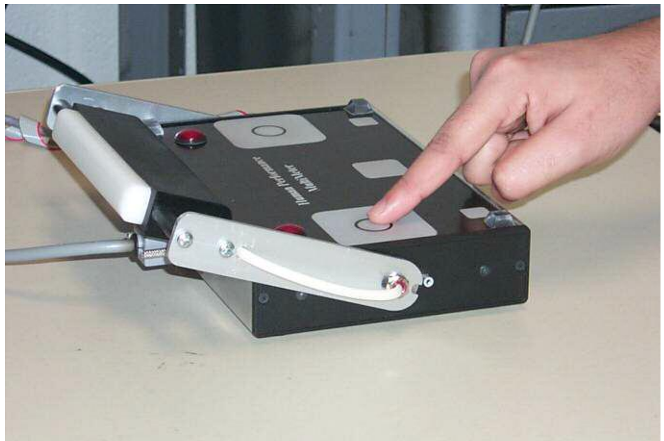

Figure 4.3 Beginning Position in a Cycle During Upper Extremity Coordination Test.

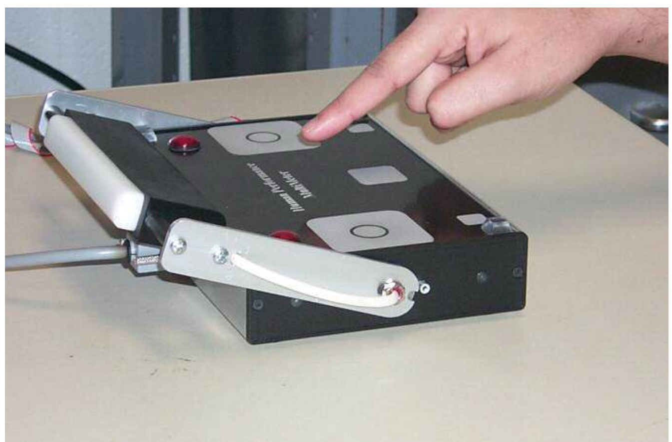

Figure 4.4 Mid-flight position.

Figure 4.5 Final Position; End of One Cycle.

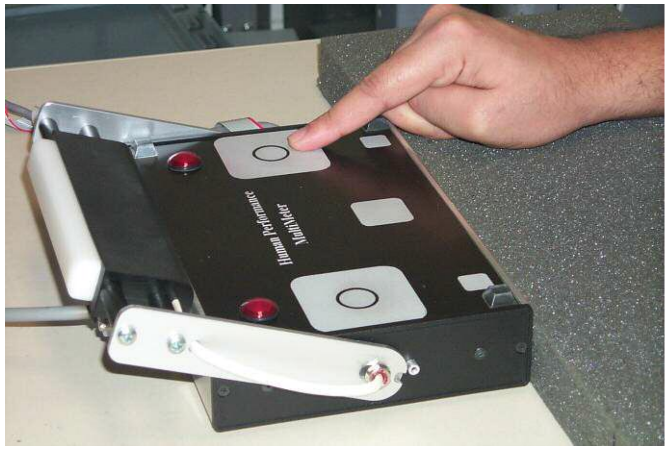

Figure 4.6 Finger Position for Finger Tapping Performance Test.

Figure 4.7 Hand-Arm Posture for Steadiness Test.

1) Simple Response Speed Test: Final result is the average of three best trials out of the five performed.
2) Rapid Alternating Movement Test: Final result is the average of two trials.
3) Neuromotor Channel Capacity Test: Final result is the average of two trials. (Note: previously, the rule used was the better of two trials.)
4) Steadiness Test: The result is the average of the best two of three trials for each of four steadiness values, namely two that are based on translational

accelerations (a_x and a_y) and two that are based on rotational rate measurements (ω_x and ω_y) . These results are then combined to construct the 4-DOF steadiness composite measure, which is defined using performance theory concepts (Kondraske 2000) as the mathematical product of the four constituent measures.

5) Grip Strength Test: Three trials are performed. The result is the average of the two best trials.

After computing final measures, descriptive statistics (mean, standard deviation, and coefficient of variation) were computed for each measure, keeping dominant and non-dominant side separately. In addition, the absolute value of the difference between Session 1 and Session 2 was computed for each subject and expressed as a percentage of the Session 1 measurement value. These values were averaged across subjects to provide a single number indicator of repeatability (e.g., mean of the absolute value of percent change).Formal reliability measures were also computed between Session 1 and Session 2. Intraclass correlation coefficients, ICC (3,1), were computed using SPSS version 12. Pearson product moment correlation coefficients were computed using Microsoft Excel 2003. The results were virtually identical for both methods; thus, only the Pearson correlation coefficient (r) is reported here.

Typically, there are differences in dominant and non-dominant side performance, with dominant side values generally higher than non-dominant side, especially for more complex tasks. To increase the measurement range over which these measures are exercised, dominant and non-dominant side data for a given measure were pooled and all analyses listed above were repeated for these data sets.

Scatter plots were also generated (Session 2 vs. Session 1) for each measure. These provide a detailed overview of all data points in the context of test-retest repeatability.

4.3 Results

Results from the analyses described are summarized in tables 4.1 and 4.2. Table 4.1 reflects results for dominant and non-dominant side data separately, whereas table 4.2 reflects the analysis results for the pooled data sets.

Note that the five GTAs which were studied produce collectively 13 different measures. These are categorized as primary, secondary and exploratory. Primary measures represent "the result" that is of most interest and possesses the characteristics, in the context of the respective test, of a true performance measurement (i.e., a larger numerical value would reflect a "better" test result. In tasks used as "test tasks" that are unidimensional with respect to performance, there is usually only one measure and it is the primary measure. Secondary measures generally reflect a particular aspect of performance in a test task where performance is multi-dimensional. In such cases, the primary measure is derived as a combination, or composite, of two or more secondary measures. For example, in the coordination test (also called the NMCC test), speed and accuracy are secondary measures used to compute the primary measure termed "neuromotor channel capacity". Another type of secondary measure is one that characterizes some aspect of a test or a condition under which it was performed. For example, the tap duty cycle mean and tap duty cycle standard deviation are characteristics of the finger tapping performance. For duty cycle, a larger or smaller duty cycle is not necessarily “better”. A smaller variation of duty cycle, however, does correspond to a “more consistent” tapping performance. This measure will be explored in the future for use in deriving a measure of consistency. Exploratory measures are termed so because they are currently under scrutiny to solidify an understanding of how they can contribute to the characterization of the performance capacity of the human subsystem involved in relevant test task. Each measure in tables 4.1 and 4.2 are marked to indicate how they are categorized. Scatter plots are presented in the context of discussion of results for each test in the following section.

Table 4.1 Summary of Experimental Results Separately for Dominant (D) and Non-dominant (N) Sides.

Measure [units]	**Side**	**Session 1**			**Session 2**			**Mean |%change|**	**Pearson (r)**
		Mean	**SD**	**CV (%)**	**Mean**	**SD**	**CV (%)**		
Isometric Grip Strength[1] [N]	D	326.2	103.6	31.7	311.9	114.7	36.8	12.5	0.86
	N	337.9	105.0	31.0	321.3	114.6	35.6	11.8	0.94
Response Speed[1] [resp/s]	D	5.39	0.43	8.0	5.59	0.53	9.5	4.9	0.83
Finger Tapping Performance Speed[1] [taps/s]	D	5.31	0.55	10.3	5.27	0.57	10.8	3.8	0.87
	N	4.82	0.52	10.8	4.84	0.52	10.7	5.0	0.83
Finger Tapping Performance Duty Cycle Mean[2] [%]	D	36.13	6.51	18.0	34.61	7.74	22.3	11.7	0.80
	N	38.71	6.08	15.7	36.72	6.74	18.3	9.2	0.78
Finger Tapping Performance Duty Cycle SD[3] [%]	D	10.75	2.00	18.6	11.36	2.48	21.7	22.0	0.24
	N	11.88	2.50	21.0	11.65	2.03	17.4	26.8	-0.25
Upper Extremity Coordination NMCC[1] [bits/s]	D	11.43	1.56	13.6	12.49	2.04	16.3	15.8	0.34
	N	9.58	1.28	13.3	9.56	1.48	15.5	12.9	0.39
Upper Extremity Coordination Speed[2] [cm/s]	D	41.87	7.94	19.0	43.81	7.02	16.0	13.5	0.54
	N	37.03	5.21	14.1	36.23	5.46	15.1	11.9	0.46
Upper Extremity Coordination Accuracy[2] [%]	D	81.75	9.42	11.5	84.05	5.58	6.6	10.1	0.19
	N	77.18	9.78	12.7	78.15	6.38	8.2	12.7	0.05
Hand-Arm Steadiness Translational Steadiness (a_x)[2] [1/g]	D	62.93	12.16	19.3	70.30	9.22	13.1	17.8	0.49
	N	63.76	9.64	15.1	69.52	9.26	13.3	12.5	0.53
Hand-Arm Steadiness Translational Steadiness (a_y)[2] [1/g]	D	84.50	17.67	20.9	93.48	14.64	15.6	20.1	0.45
	N	83.22	13.15	15.8	91.70	15.20	16.6	13.4	0.68
Hand-Arm Steadiness Rotational Steadiness (ω_x)[2] [s/deg]	D	1.19	0.30	25.4	1.20	0.30	24.6	12.8	0.79
	N	1.21	0.34	28.1	1.21	0.42	34.3	14.6	0.80
Hand-Arm Steadiness Rotational Steadiness (ω_z)[2] [s/deg]	D	0.83	0.32	38.8	0.90	0.35	38.2	16.8	0.85
	N	0.77	0.31	41.5	0.87	0.44	49.9	22.3	0.89
Hand-Arm Steadiness 4 DOF Steadiness[1] (a_x, a_y, ω_x, ω_z) [SUs]	D	5979	4645	77.7	8302	6279	75.6	82.9	0.63
	N	5880	6465	110.0	9007	11482	127.5	57.5	0.95

[1]Primary measure [2]Secondary measure [3]Exploratory measure

Table 4.2 Results of Analysis with Pooled Dominant and Non-dominant Side Data.

Measure [units]	**Session 1**			**Session 2**			**Mean |%change|**	**Pearson (r)**
	Mean	**SD**	**CV (%)**	**Mean**	**SD**	**CV (%)**		
Isometric Grip Strength[1] [N]	319.0	108.2	33.9	329.6	108.9	33.0	12.2	0.91
Finger Tapping Performance Speed[1] [taps/s]	5.06	0.58	11.5	5.06	0.58	11.5	4.4	0.87
Finger Tapping Performance Duty Cycle Mean [2] [%]	37.42	6.35	17.0	35.66	7.24	20.3	10.5	0.80
Finger Tapping Performance Duty Cycle SD[3] [%]	11.31	2.30	20.4	11.50	2.24	19.5	24.4	0.01
Upper Extremity Coordination NMCC[1] [bits/s]	10.50	1.69	16.1	11.02	2.30	20.9	14.4	0.59
Upper Extremity Coordination Speed[2] [cm/s]	42.84	7.46	17.4	36.63	5.28	14.4	16.6	0.58
Upper Extremity Coordination Accuracy[2] [%]	82.90	7.73	9.3	77.66	8.16	10.5	10.1	0.36
Hand-Arm Steadiness Translational Steadiness (a_x)[2] [1/g]	63.34	10.84	17.1	69.91	9.13	13.1	15.2	0.50
Hand-Arm Steadiness Translational Steadiness (a_y)[2] [1/g]	83.86	15.39	18.4	92.59	14.76	15.9	16.8	0.54
Hand-Arm Steadiness Rotational Steadiness (ω_x)[2] [s/deg]	1.20	0.32	26.5	1.21	0.36	29.5	13.7	0.80
Hand-Arm Steadiness Rotational Steadiness (ω_z)[2] [s/deg]	0.80	0.32	39.7	0.89	0.39	43.7	19.6	0.87
Hand-Arm Steadiness 4 DOF Steadiness[1] (a_x, a_y, ω_x, ω_z) [SUs]	5930	5557	93.7	8655	9141	105.6	70.2	0.85

[1]Primary measure [2]Secondary measure [3]Exploratory measure

4.4 Reliability and Validity of HPMM Measurements

There are two aspects to the evaluation of measurements obtained by using the current HPMM prototype: their reliability and their validity. For each test, these aspects of the corresponding measures are discussed in that order.

With regard to repeatability and the way in which it is classically measured, it should be mentioned here that members of the subject pool are all young and healthy, resulting in the "exercising" of these measurements over a rather narrow segment of the range over which they are intended to measure. However, this population represents that which could be considered "the most stable"; i.e., repeat performance is not influenced by medication metabolism, disease processes, etc. Nonetheless, actual performance in maximal performance tests does vary even in this population. Thus, reliability measurements are performed under worst-case conditions. This issue has been discussed previously (Sriwatapongse, 2002; Mayer et al, 1997) and is reiterated here due to its importance. Because the subjects are all young and healthy, the range of their performance for many of the measures is relatively small and the variation within a subject is a large fraction of the variation within a population. This situation makes it more difficult to obtain high reliability coefficients. In cases where the distribution of a measure covers a wide range such as grip strength, it is generally easier to obtain higher reliability coefficients.

To investigate validity, the agreement between these results and those obtained with earlier versions of the HPMM, as well as those obtained with laboratory based instruments, must be checked. In addition, the presence of “expected patterns” is also illustrative of validity (e.g., better performance on the dominant side, when anticipated).

Perfect agreement is not expected in these evaluations since data from different subjects is being compared. Some of the measurements hitherto reported using comparable laboratory instruments are also slightly different, sometimes in terms of the approach to the measurement itself, and at other times in trivial areas such as the unit used. For example, isometric grip strength was sometimes reported with units of pounds, and since the introduction of the HPMM, is measured in newtons. The earlier versions of visual response tests measured and analyzed data in response times, but we now measure this quantity as response speed. In such cases, results may easily be converted from their ‘old’ units to newer ones for comparison with present results. In cases such as that of the steadiness test, where measurement was earlier made using a non-contacting capacitive displacement transducer, a mathematical transformation needed to be performed because previous versions of HPMM used a measure of acceleration as the basis for computing steadiness performance. In other words, displacement-based steadiness results had to be converted to acceleration-based steadiness. Another measurement, the rotational rate-based steadiness, did not exist prior to the current (fourth generation) HPMM prototype. However, in all measurements except rotational steadiness, a reasonable direct comparison of results from third and fourth generation HPMM systems can be made. Finally, it should be noted that while strong agreement between these two generations would likely contribute to validity of measures, disagreement must be carefully evaluated, as it would not be clear which version (if not both) represented "the problem".

4.4.1 General Observations

Comparisons to data obtained from laboratory based instruments (Potvin, Tourtellotte et al., 1985) shows good agreement for tests such as visual response speed, isometric grip strength, neuromotor channel capacity and finger tapping speed (generally, the GTA is called "rapid alternating movement speed").

4.4.2 Isometric Grip Strength

The results for this test show good test-retest reliability. The Pearson correlation coefficients of 0.86 for dominant and 0.94 for non-dominant sides are high and closely match those obtained using version 3 of the HPMM. The grip strength scores also fall in an expected range for the subjects tested, which has been established using laboratory based instruments as well as the previous version of the HPMM. The scatter plot of Figure 4.8 shows points that are rather tightly distributed about the ideal line.

Comparison of mean grip strength shows that these measures are in good agreement with previously obtained values (Figure 4.9). Overall, these evaluation results are important. The grip strength measurement performed with the current version incorporated the grip strength sensor into the handle of the HPMM. This is therefore the first evaluation of this type of packaging, which reflects final design packaging. In addition, the test instructions (see Appendix A) have been modified to improve grip strength measurement in extremely weak subjects and also to facilitate test administrator interaction with the HPMM user interface. The good reliability and the finding of measured performance in the expected range for this population are encouraging in light of the incorporation of these new features.

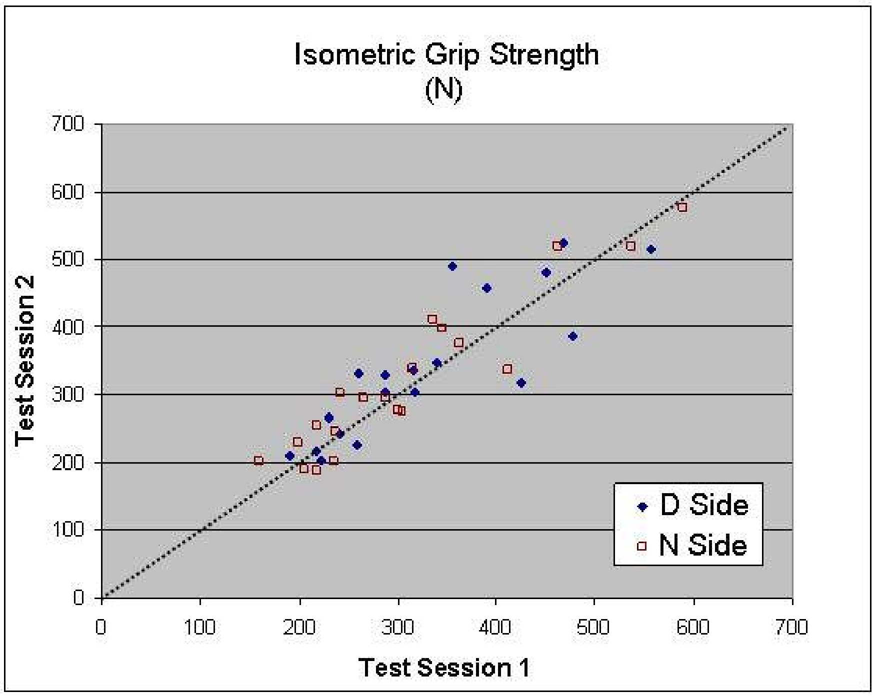

Figure 4.8 Comparison of Grip Strength results from the two test sessions.

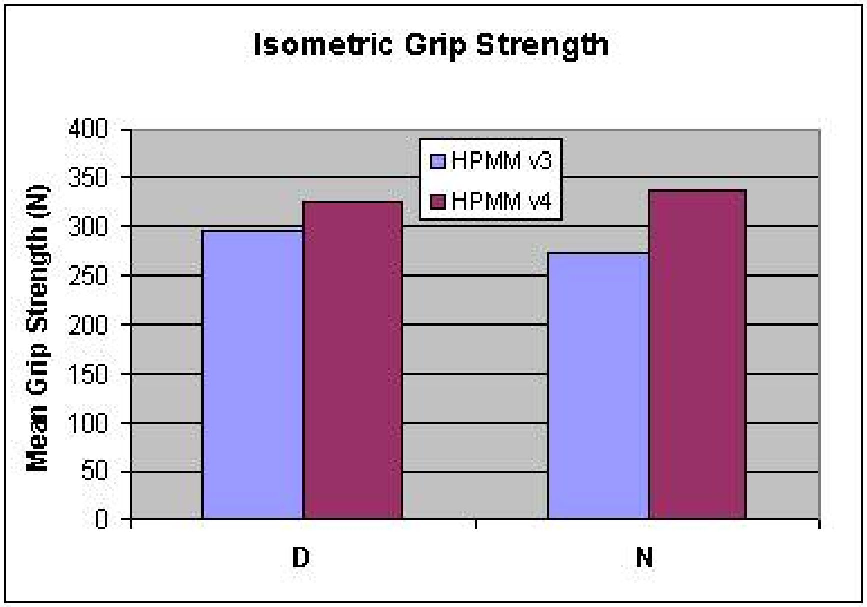

Figure 4.9 Comparison of Grip Strength results from HPMM versions 3 and 4.

4.4.3 Visual Response Speed

Since this test focuses on central processing, it is not considered to be "side dependent" and is thus performed using only the dominant hand as a "participant", but not the system of focus, in the test. The results of these measurements show clear test-retest reliability with a high Pearson coefficient of 0.83. Measurements also fall within the expected range and compare well with previously obtained values. Figure 4.10 shows a comparison of results from the two test sessions.

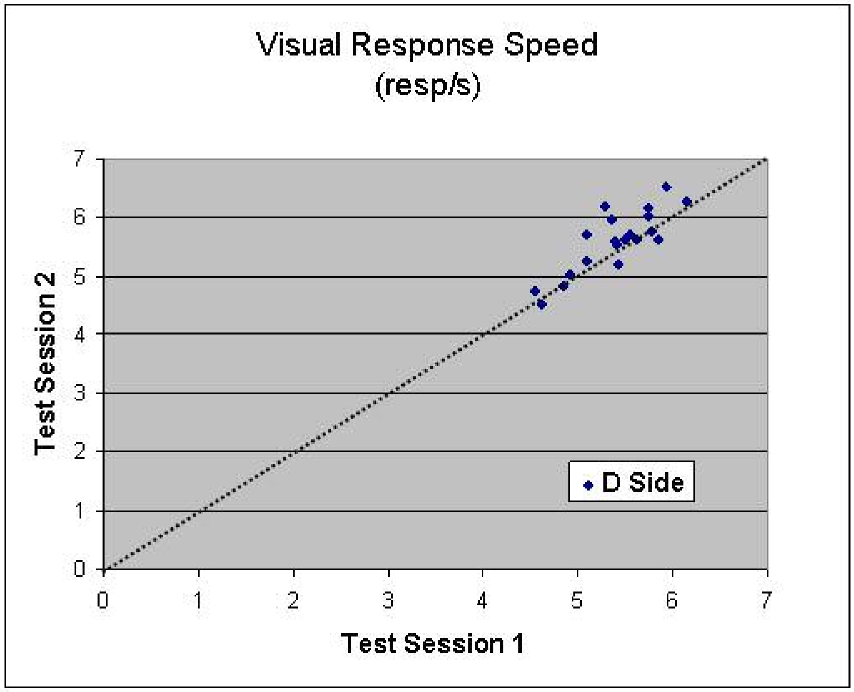

Figure 4.10 Comparison of results from two sessions of the visual response speed test.

4.4.4 Finger Tapping Performance

The generic test involved here is termed "rapid alternating movement" performance, which was applied here to focus on finger tapping (with motion restricted to flexion and extension about the metacarpophalangeal joint of the index finger). The primary measure is the tapping speed (taps/s), which has been used extensively by many researchers (Potvin et al, 1985). Tap duty cycle mean (%) is a secondary measure and the standard deviation of the tap duty cycle (%) is an exploratory measure.. While more importance is currently attached to the primary measure, the other two are also evaluated.

The tapping speed results display good inter-session repeatability (r = 0.87 and 0.83 respectively for dominant and non-dominant sides). Also, there is a very good agreement between the mean values of tapping speed obtained by the present and previous versions of the HPMM in which similar populations were involved

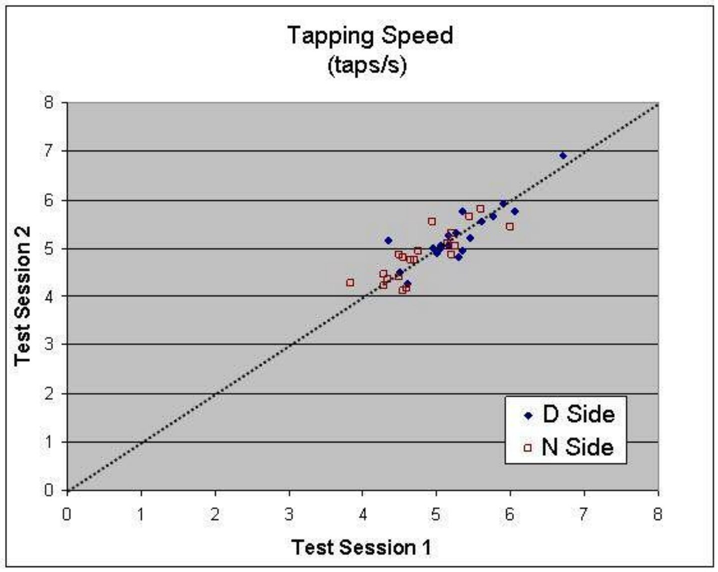

Figure 4.11 Comparison of primary measure results from two sessions of the finger tapping performance test.

High test-retest reliability is demonstrated by the tap duty cycle mean measurements, but low ($r < 0.3$) values are shown by the tap duty cycle standard deviation. One possible reason is that the subject pool consists only of healthy individuals and the inter-subject variability for this measure is quite low relative to the range over which this parameter can vary across all subject types of interest.

4.4.5 Upper Extremity Coordination

Repeatability for the primary measure in this test, i.e. neuromotor channel capacity (NMCC), was the weakest of all measures studied. This finding was also similar to that found during version 3 evaluations (version 3 vs. version 4: $r = 0.36$ vs. $r = 0.34$ for the dominant side and $r = 0.6$ vs. $r = 0.39$ for the non-dominant side). This again may be due to narrow distribution of this performance in the subject pool, as discussed elsewhere. Supporting this, the reliability increased ($r = 0.6$) when dominant and non-dominant side data was pooled to create a larger measurement range. In a clinical context where pathologic patients will be involved, the ability to discriminate healthy and poor performance is thus likely to be rather good.

There is also one outlier data point produced by a subject who exhibited an excessively high score for NMCC during Session 2. This score is currently not explainable and may be due to a subtle, data-dependent software error. A higher Pearson coefficient ($r = 0.5$) was obtained when the analysis was performed excluding this subject's reading. Other issues related to NMCC reliability are discussed in Chapter 5.

The NMCC values are in good agreement with those obtained from previous studies. The index of task difficulty ensures that the contribution of change in instrument dimensions is adequately factored in so that the subject's score will be primarily dependent on their speed and accuracy. The mean scores for both dominant and non-dominant sides are about 10-15% higher than those obtained with HPMM version 3 (Sriwatanapongse, 2002). The touch sensor subsystem has been completely redesigned in version 4 (see Chapter 3) and is more likely to provide more accurate registration of tapping. Also as noted previously, the expression used to compute NMCC from speed and accuracy measurements is also slightly different. Scatter plots are also included for the secondary measures of speed (figure 4.13) and accuracy (figure 4.14). However, since speed and accuracy may trade-off, it is neither necessarily expected nor desirable that these values remain the same on retest.

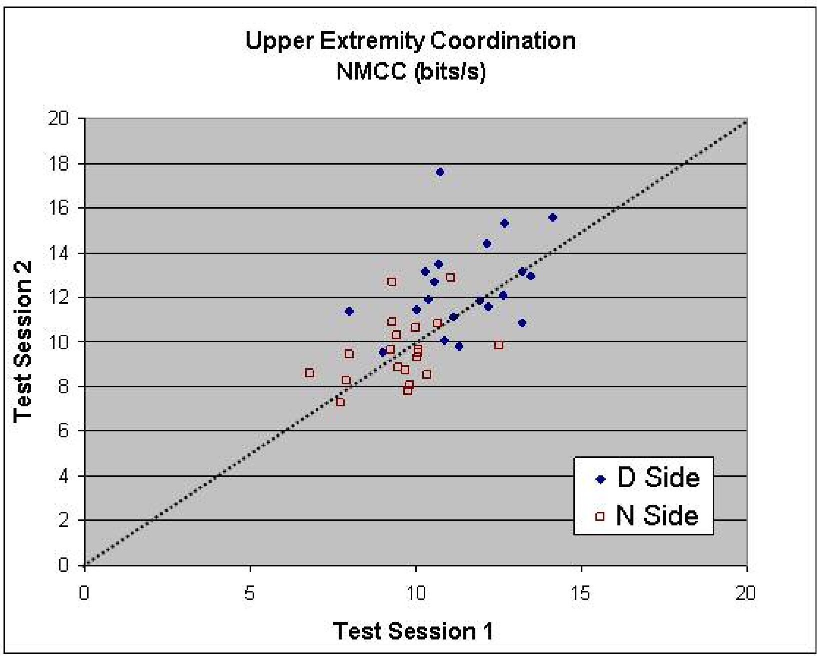

Figure 4.12 Scatter plot for NMCC measurements between the two test sessions.

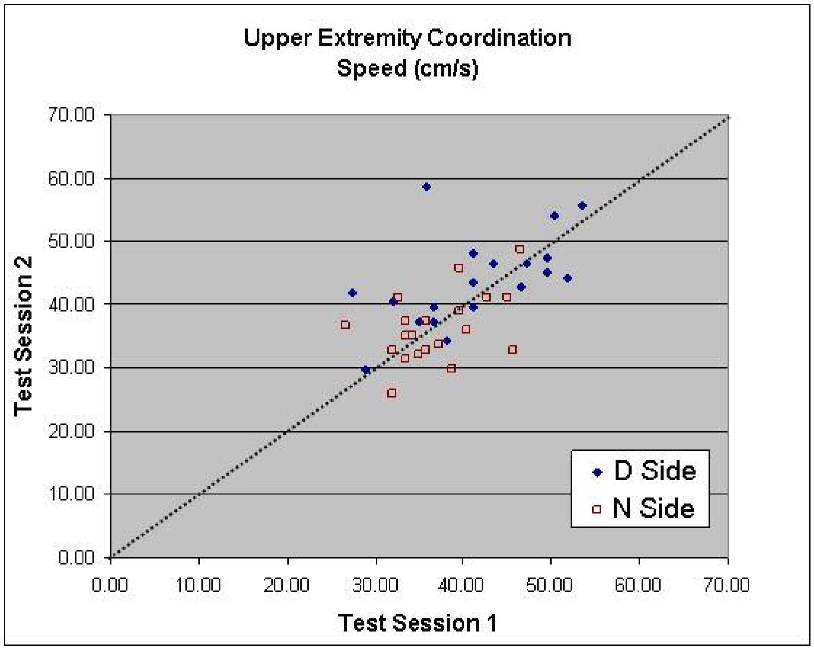

Figure 4.13 Upper Extremity Coordination Speed scores for sessions 1 and 2.

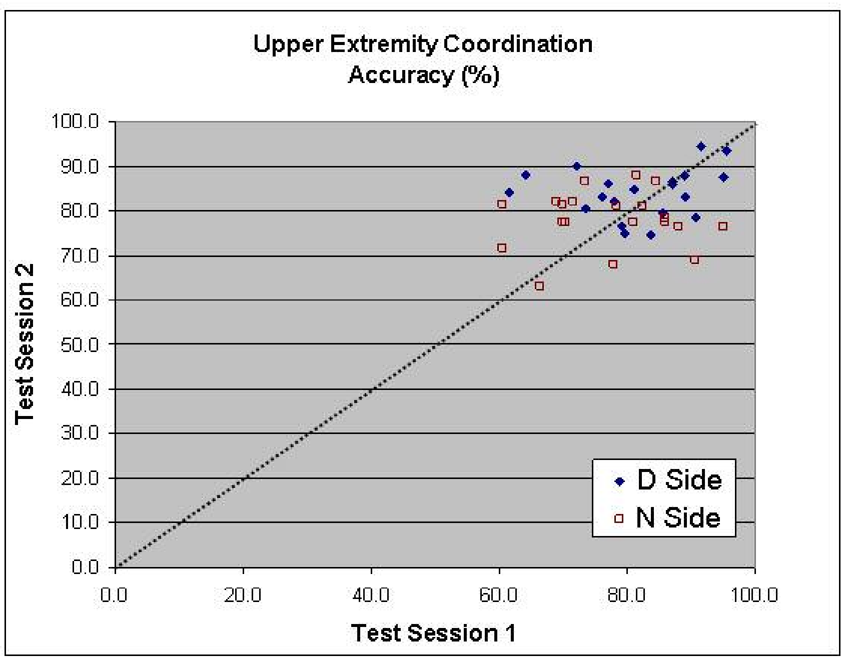

Figure 4.14 Upper Extremity Coordination Accuracy scores for two test sessions.

4.4.6 Hand-Arm Steadiness

The results of this test include four constituent components and one composite measure as discussed in section 4.2. The four constituent components represent 4 degrees of freedom (with regard to the motion of the body part involved). The final one which is obtained by multiplying the first four together is called the 4 degree of freedom (4-DOF) steadiness.

Before the work done in this thesis, the HPMM incorporated only translational acceleration as the basis for steadiness measurement.. Hence, no direct retrospective comparisons can be made. Proceeding in this fashion,

There is a good agreement between the translational steadiness values obtained by the present and previous versions of the HPMM (figure 4.15). However, the laboratory based measurements were primarily displacement oriented. A detailed treatment on the conversion of the acceleration based results to a displacement based form has been provided in (Sriwatanapongse, 2002). The author there found close agreement between the results obtained using the two types of measures. Hence, one can state by inference that the present version of the HPMM has provided results that are also in close agreement with the classic laboratory based instruments' results. It is noted that these measurements involve very small motions in healthy subjects that approach the current noise floor of the instrumentation. Nonetheless, as figures 4.16 and 4.17 illustrate, the system is able to discriminate differences in the steadiness of healthy subjects with good repeatability (i.e., for the most part, those who are least stable during Session 1 are the least stable during Session 2 and vice-versa).

Along the y axis, the average translational steadiness of the subjects is higher than that along the x axis (figure 4.16). This is somewhat unexpected because more movement results in the y direction when the RSM is mounted on a subject's hand according to the procedure for this test (see Appendix A). Upon further investigation, this anomaly is attributed to the fact that the noise levels on the x axis output of the sensor are slightly higher than those on the y axis output. Chapter 5 discusses a possible remedy for this situation. The test-retest repeatability of the x-axis translational steadiness is comparable to that of the y-axis translational steadiness as indicated by their Pearson correlation coefficient values (in Table 4.1). The coefficients themselves are somewhat higher than those obtained with version 3. They are surprisingly high given that the number of degrees of freedom in motion, providing a wide variety of ways in which a subject could conceivably exhibit the same "amount" of overall steadiness upon repeat testing.

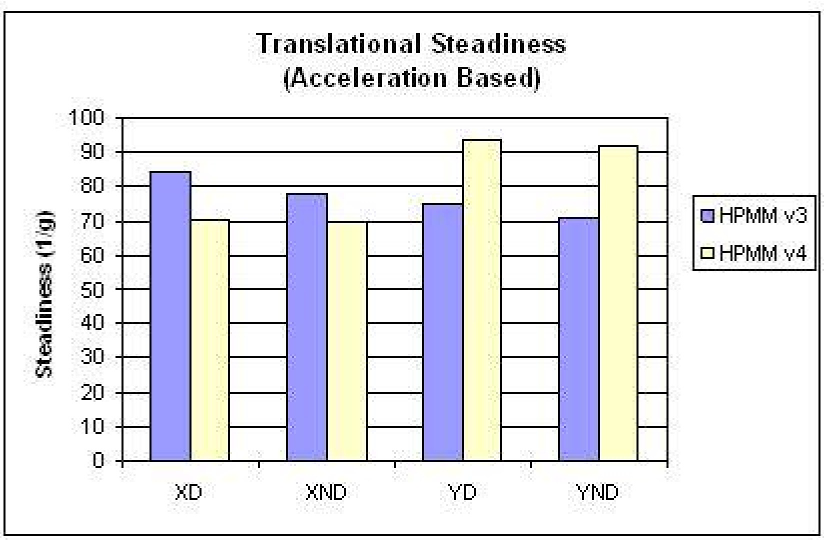

Figure 4.15 Comparison of Steadiness Values from present and previous HPMM versions.

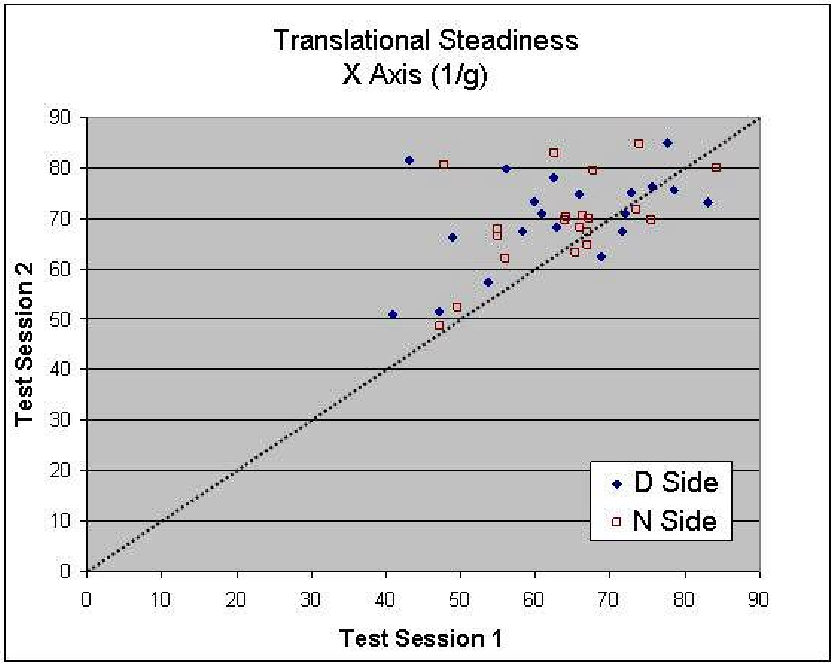

Figure 4.16 Comparison of sessions 1 and 2 for translational steadiness – X axis.

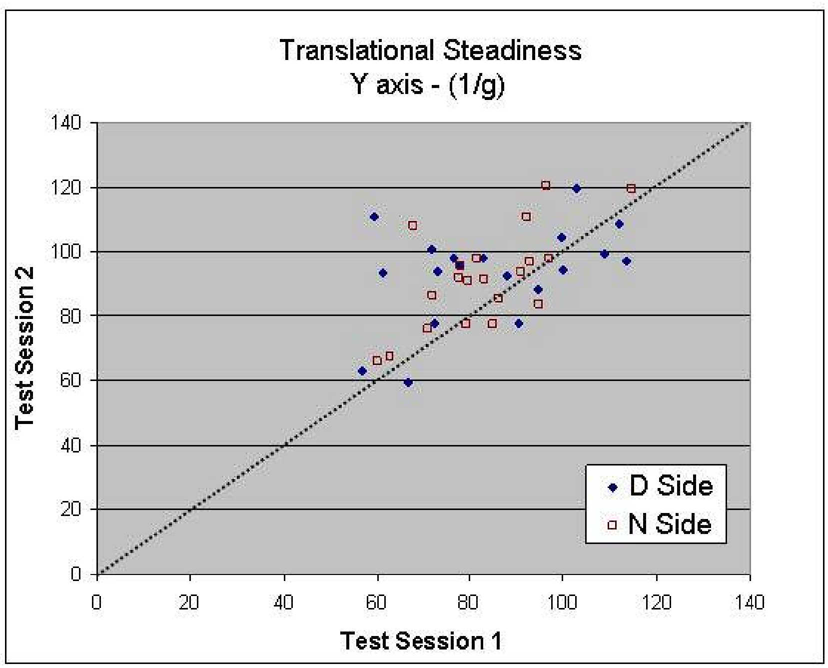

Figure 4.17 Comparison of sessions 1 and 2 for translational steadiness – Y axis.

As noted, the rotational rate-based steadiness measures are new in this version of the HPMM. When mounted on the hand, as was done in the current study, the motions of wrist flexion-extension (rotation about the RSM "x" axis) and forearm pronation-supination (rotation about the RSM "y" axis) are measured. These measurements display higher test-retest reliability than the translational steadiness measurements ($r > 0.8$).These values are again surprisingly high given that we are looking at only one DOF at a time and multiple DOFs are present, suggesting that subjects tend to achieve a given amount of steadiness "in the same way" upon repeat maximal performance testing. That is, subjects who have little rotational wrist flexion-extension motion and high translational motion in a vertical direction tend to always exhibit this pattern. While no data exists in the HPMM context for comparison of values obtained, there is a commercial device (Motus tremor measurement system) that does utilize an angular rate sensor for similar measurements. This Motus unit only incorporates a single degree of freedom sensor, whereas the HPMM version 4 senses two angular DOFs as described above. Thus, two separate tests must be done, with the Motus sensor mounted differently each time, to evaluate both DOFs of interest. The opportunity to access one of these systems provided the basis for a preliminary, crude evaluation of the range of values that were obtained in the present study. Data from the Motus system for the dominant hand of a single healthy male subject showed (Kondraske, 2005) the equivalent rotational steadiness for wrist flexion-extension of 1.27 s/deg (compared to 1.19 s/deg for the HPMM) and for forearm pronation-supination of 0.93 s/deg (compared to 0.83 s/deg). For both the HPMM and Motus data, steadiness was better for wrist flexion-extension than for forearm pronation-supination motion. Finally, it is desirable to have one single number that can represent the steadiness of a subject, rather than four numbers. This necessity motivated the development of 4-DOF steadiness according to the rules of the General Systems Performance Theory where the dimensions of the four constituent quantities are preserved. This is accomplished by multiplying the four quantities together. The resulting 4-DOF steadiness numbers have been observed to possess a very good degree of test-retest reliability. Since each of the constituent components appears to have a reasonable degree of validity (i.e., no anomalies were observed in the numerical values of the two translational and two rotational constituent components), it is reasonable to attribute at least a basic level of validity to the composite 4-DOF steadiness measure.

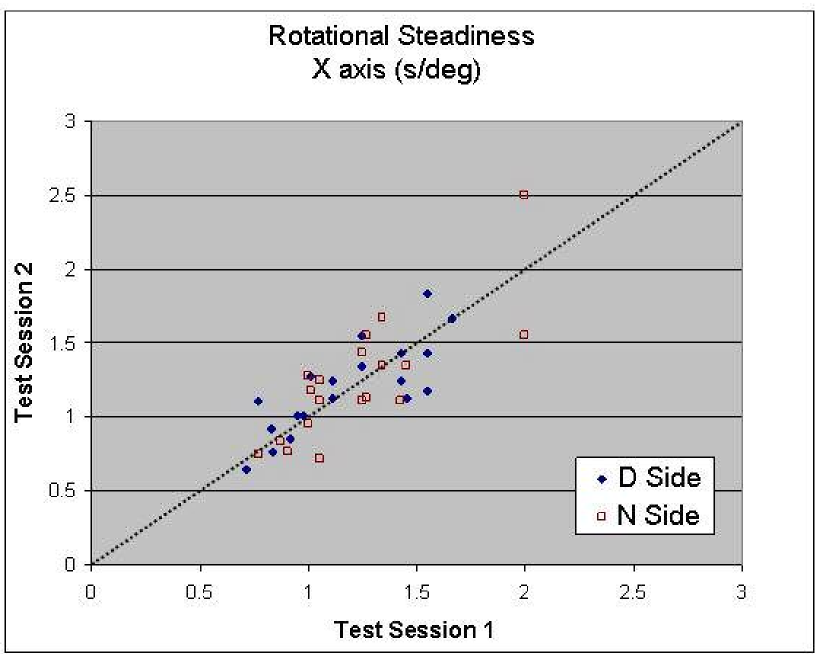

Figure 4.18 Rotational Rate Based Steadiness – X axis; comparison between sessions.

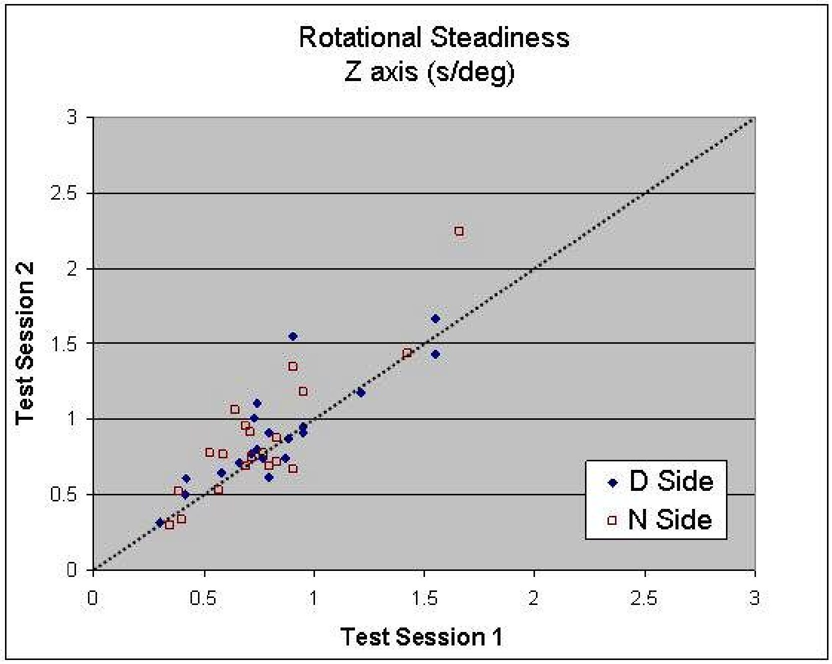

Figure 4.19 Rotational Rate Based Steadiness – Z axis; comparison between sessions.

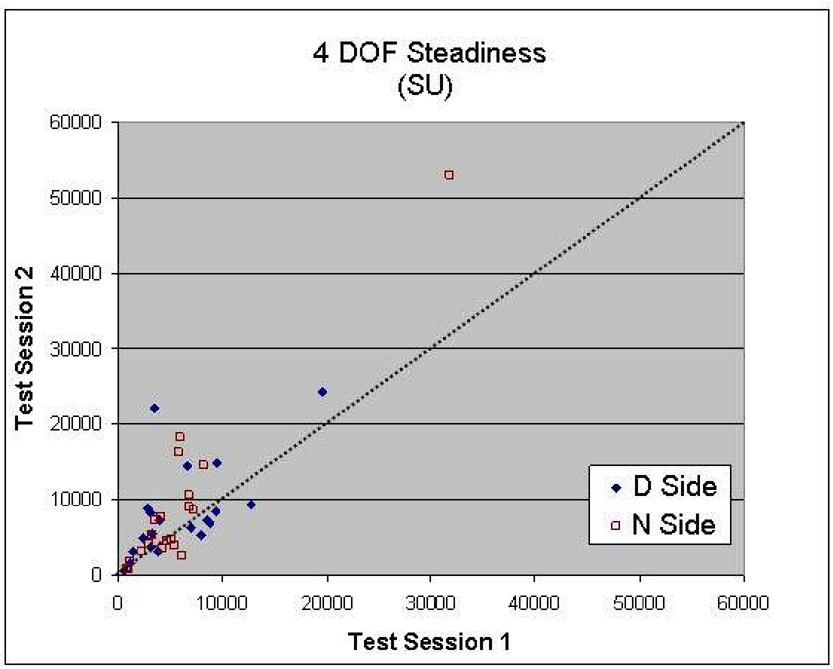

Figure 4.20 4-DOF Steadiness; comparison between the two sessions.

One may notice from figures 4.18 and 4.19 that there is a fairly tight distribution of points around the ideal line except for one outlier. This person with high rotational rate steadiness has influenced the 4-DOF steadiness result by causing an outlying point in the scatter plot for this measurement as well, which is reflected in figure 4.20.

CHAPTER 5

CONCLUSIONS AND FUTURE RESEARCH

The work in this thesis represents the most recent phase in the development and continued evaluation of a portable, packaged, and functional fourth generation prototype of the HPMM. Selected performance capacity tests implemented on this platform to gauge reliability and validity of each. The following objectives of the thesis, which were presented in chapter 1, have been achieved:

1) Studied the previous version of the HPMM and relevant laboratory based instruments from architectural and functional perspectives. Studied the documents that described the present version of the HPMM and made improvements to them.
2) Modified the earlier version of the HPMM operating system software to create a new version that runs on the current HPMM hardware platform and included routines that drive the touch screen and LCD.
3) Verified the performance of new sensor subsystems such as accelerometer, angular rate sensors and touch sensors. The new force sensor subsystem was packaged into the HPMM handle.

4) Proposed a method of combining the four secondary results of the steadiness test into one primary result called the four degree of freedom (4-DOF) steadiness.
5) Reviewed and implemented the five GTAs namely: isometric grip strength, simple visual response speed, rapid alternating movement, upper extremity coordination and hand-arm steadiness in strict conformance to the procedures dictated by the HPI internal documentation.
6) Evaluated the performance of the HPMM in its intended packaging.. Administered the five performance tests to twenty healthy subjects. Analyzed the large amount of data thus collected and performed statistical tests using specialized software. Special emphasis was laid on test – retest repeatability. The validity of the measurements was investigated by comparison with previously obtained data through the previous HPMM prototype as well as laboratory based instruments.
7) Provided recommendations for future work in section 5.2

5.1 Conclusion

After the experience of the experiments described in chapter 4, it is concluded that the performance of the aspects of the system tested is satisfactory. The instrument was convenient to use in the Generic Test Mode. More importantly, very good test-retest reliability has been found for all measures except for neuromotor channel capacity. When dominant and non-dominant side data were pooled, reliability of all measures improved, with neuromotor channel capacity test-retest reliability approaching acceptable levels. Validity of the results associated with the five generic tests studied was also supported by the fact that the values obtained for respective measures were in good agreement with the results obtained from laboratory based instruments and the previous prototype version of the HPMM. It is thus concluded that the primary goal of this thesis has been achieved. A set of important performance capacity tests have been implemented on a new hardware platform in a final-packaged, portable, functional prototype of the HPMM and, with minor exceptions, the current set of measurements have been demonstrated to exhibit good reliability and encouraging validity.

5.2 Recommendations for Future Research

There are a good number of positive results that have been obtained for this realization of the HPMM. However, further improvements may be considered. The following is a discussion of those issues which emphasize the system in general and issues that pertain to the five generic tests studied. Discussion of completely different generic tests is beyond the current scope.

The gain of the accelerometer and angular rate subsystems requires further investigation in order realize optimal performance with the widest possible range of subjects. When these are used as components of steadiness measurement, an increased gain would permit small accelerations and angular rates to be better resolved. The present gains were optimized to avoid saturation for very large pathologic tremors, while still attempting to provide a reasonable ability to resolve small motions such as those present normally in healthy subjects. In addition, the use of these sensor channels for other tests which impose different gain requirements was also considered. Currently, signals from pathologic subjects, such as those who exhibit symptoms like tremor, lie far above the system noise floor. However, small inputs typical of healthy subjects lie close to the noise level and cannot therefore be measured with the same accuracy.

It is recommended that an auto-ranging capability be explored for these signals when used in the context of steadiness measurement. The version 4 hardware architecture allows for this type of function which can be implemented by digitizing both the DC-coupled (low gain) and AC-coupled (high gain) signal paths in the acceleration and angular rate sensor subsystems during the course of a timed steadiness test. Thus, the gain for the AC-coupled path could be increased over its present value to improve resolution of small signals and the threat of saturation can be avoided. Processing can use the low-gain DC-coupled channel for large signals (i.e., whenever saturation is approached on the high gain AC-coupled channel. The fact that the DC-coupled channels are not high-pass filtered is not as critical for large signals, as DC errors contributed would be relatively small when expressed as percentage of typical signal amplitudes. It is necessary to preserve DC-coupled channels from each of these sensors in order to support other tests planned for HPMM incorporation.

Another possible improvement with regard to the acceleration and angular rate measurement subsystems could be made with regard to calibration. While these sensors are presently being calibrated only for offset, it is recommended that the calibrations be performed for sensitivity (gain) as well. This will help to make the subsystems more accurate as the overall system design will be able to account for sensor manufacturing variability.

In the version 4 hardware platform, the touch sensor design was changed from version 3 to version 4. In version 3, a central target was surrounded by an “error ring”. In version 4, this ring was divided into two lateral regions (that are electrically connected to each other) and a fore and an aft region (i.e., above and below the target) which are also electrically connected. The ability to distinguish the type of errors made was not exploited in the current version. In the future versions of the NMCC test algorithm, it is proposed that a distinction be made and the errors be classified as lateral or fore-aft errors. The only change would be to include at least one additional secondary measure: lateral-to-fore aft error ratio. There is currently no basis for knowing what value of this quantity would be considered “normal” or “better”, although it would seem that a random distribution would be found in healthy subjects and the thus a ratio of approximately 1.0 might be expected.

Another issue has been noted in relation to the upper extremity coordination test. It appears that stopping the test exactly after ten seconds results in having some subjects lose a ‘cycle’ if at the end of the tenth second, the finger is in mid-flight en route to the touch sensor. It is proposed that the test be stopped after the completion of the flight cycle in progress when the ten second test duration elapses.. It is also recommended that three trials be taken for side (dominant, non-dominant) during a test session, and the average of the best two trials be considered the result for that session. These changes should improve the reliability of the coordination measurements.

With regard to the finger tapping performance test, consideration should be given to sampling touch sensors at a much faster rate (about 1 KHz, so that time samples are 1 ms apart). This will allow for increased accuracy in measurements such as the duty cycle standard deviation, which in the current situation has been shown to exhibit low reliability Use of the optional 256 KB external memory chip will allow the storage of the much larger number of touch sensor samples that will result from the increased rate.

Power management issues have been dealt with in an efficient manner with a well designed power subsystem that includes dc/dc converters and low drop-out (LDO) linear regulators. A battery charger subsystem is present on the version 4 main unit, but it was not exercised as part of this thesis work. Another facility that will be planned upon is the implementation of a sleep/wake-up power management mode. Inactivity lasting longer than fixed time duration will cause the HPMM to go into this power save mode.

A speech processing subsystem has been designed and the hardware implemented. Software needs to be written in order to utilize its capabilities and hence implement the speech and audio performance tests. Digital speech processing algorithms that are required for extra desired measures can be implemented on the fast HPMM microcontroller with an anticipation of good performance.

The touch screen currently serves as the user input device and generally performed well. However, this subsystem has numerous programmable parameters that affect its performance and these aspects should be studied to determine optimal responsiveness (i.e., the best balance between being "sensitive enough" yet not overly sensitive so as to generate false detections from glancing touches). Appropriate software-based timer based routines similar to those used in switch debouncing may be helpful. Vigorous testing needs to be done to make sure that a smooth operation is achieved in situations like menu scrolling.

As noted previously, the Protocol Driven Mode was not implemented on the version 4 platform. Given that a basic operating system is now implemented and has been reasonably exercised, a reasonable goal would be to implement the Protocol Driven Mode (see chapter 2) supporting protocols that consist of combinations of the five generic tests that have now been implemented.

APPENDIX A

HPMM VERSION 4: INSTRUCTIONS TO TEST SUBJECTS AND EXAMINERS

GTA 1: ISOMETRIC STRENGTH TEST

INSTRUCTIONS TO SUBJECT:

- This test will measure the strength of the group of your muscles that is used in producing a grip with your hand.
- Sit on this chair facing me.
- I will hold the device like this and ask you to squeeze the handle.(examiner: grasp the long edges of the HPMM with one edge in each of your hands and the force sensor handle vertical. Hold the device at a level above the floor so that the subject's forearm is approximately parallel to the floor.
- Try to squeeze the device now so you may get a feel for it. During the test, you will need to squeeze as hard as you can for about three seconds. Do not push toward me or pull toward you; just squeeze.
- OK, now that you are familiar with the procedure, we will run the test. (Press the touch screen button to start the test and then hold the instrument in front of the subject).
- When you hear a beep, you may start squeezing as hard as possible for about three seconds, then relax. I will verbally urge you to squeeze as hard as you can during the test. Upon completion you will hear a double beep.
- We will do this trial twice.

INSTRUCTIONS TO THE EXAMINER

- Configure the HPMM so that the force sensor handle is above the touch sensor panel and locked in this position.
- Select "Isometric Strength Test" from the menu and proceed up to the point where the next touch screen entry will start the test.
- Give the subject the opportunity to become familiar with the device and procedure before initiating the actual test (see above).
- Then press ENTER on the touch screen to initiate the actual test, and carefully hold the HPMM in front of the subject as described above.
- A beep will sound; ask the subject to squeeze while applying maximum possible force for 3 to 5 seconds.
- Encourage the subject while squeezing by saying "Squeeze...Squeeze...Squeeze (in about 1 sec intervals) Ok Stop". Be sure that the subject only squeezes and does not push toward you or pull away from you during the test. Use your own control of the instrument to balance out push or pull forces while the subject squeezes.
- When finished, ask subject to relax. Press REPEAT on the HPMM screen to repeat the test.

GTA 2: SIMPLE VISUAL RESPONSE SPEED TEST

INSTRUCTIONS TO SUBJECT:

- Place your finger on this region here (direct subject to home sensor region).
- You will hear a beep which indicates the start of the test.
- In any time between one and three seconds, both these red lights will light up. As soon as this happens, you must lift your finger off of the region.
- When you lift your finger off the region, make sure you move your entire arm and not just your finger or wrist.
- Do not try to guess as to when the lights will come on.
- Once you are done lifting the finger off the region, place it back there for the next trial.

INSTRUCTIONS TO EXAMINER:

- Flip the HPMM over and show the home sensor to the subject.
- Make sure the subject is seated with their arm in line with the home sensor.
- Show the subject how to take their finger off the home sensor using their entire arm. The motion must be about the elbow and not the knuckle or wrist. Cancel any trial in which the subject fails to do this properly.
- Allow the subject to practice the movement and start the test only when you are confident of their correctness.
- When the subject is positioned properly, select READY. A beep will sound only when the HPMM detects the subject’s finger on the sensor.
- If the subject tries to guess the turn on time of the lights and wrongly lifts the finger, an anticipation error is detected and the lights will flash repeatedly. Ask the subject to replace the finger on the home sensor region to redo the trial.

GTA 4: RAPID ALTERNATING MOVEMENT

INSTRUCTIONS TO SUBJECT:

- This test will examine how fast you can move your index finger about your knuckle.
- Place your hand here and first make a fist, then extend only your index finger like this.
- Using the pad of your index finger, you must tap within this square region (point region outline to subject).
- Your finger may fall anywhere within the region. Lift your finger about 1 inch from the plate during each tap.
- A single beep will begin the test but the timing will begin after your first tap. A double beep will signal the end of the test.
- Ensure that your movement is about your knuckle only. Do not curl your fingers or flex your wrist.

INSTRUCTIONS TO EXAMINER:

- First, flip the HPMM to show the subject the required touch sensor areas.
- Have the subject go through the required motions for a few seconds and select the most comfortable position. Usually, this is with the forearm resting on the examination table, the HPMM shifted toward the side of the involved arm and placed further back on the table, and with either one of the left or the right touch sensor regions under the subject's finger.
- Encourage the subject so that the best effort is made continuously. Be sure that the subject keeps his or her finger stiff, that flexion occurs only at the knuckle and that the finger is definitely lifted (not wiggled around) each tap cycle.
- Some subjects may have difficulty obtaining distinct lifts, but it will be apparent that additional speed is not being gained. Others will try to gain a speed advantage by staying very close to the plate.
- Interrupt the test, give the subject a short rest, and start over if necessary to obtain compliance.

GTA 5: UPPER EXTREMITY COORDINATION TEST

INSTRUCTIONS TO SUBJECT

- The purpose of this test is to measure your ability to make coordinated movements with your hand and your arm.
- We will use these two regions of the HPMM. Each of these (left and right) has a target and an error region (show regions).
- Should your finger land on the target region, it will count as a hit. A landing on the error region will count for a miss.
- Use the pad of your index finger to alternately tap between these left and right regions ‘as fast as you can while making no errors’. That is the goal for this test.
- You will hear a beep when its okay to start tapping, and the test will begin with your first tap. It will last 10 seconds and a double beep will signal the end of the test.
- Remember that both your speed and your accuracy will go into calculating your score. So do your best.

INSTRUCTIONS TO EXAMINER

- Flip the HPMM over and show the subject the target and error regions.
- Position the subject's chair and test module so that the shoulder of the arm involved is centered on the module.
- Thus, when the right arm is used, the module center will be slightly to the right of body center, and vice-versa.
- After selecting READY, a single beep will occur and you may ask the subject to start tapping between. A long beep will ensue if for some reason the subject stops tapping for longer than 3 seconds. The test will automatically restart.
- Since this test involves a trade off between speed and accuracy, the best score is obtained when the subject is going fast enough to make a few errors. Therefore, the subject's final score should show somewhere between a 5-25% error factor (75-95% accuracy).
- Some impaired subjects may not be able to obtain error rates this low. You should watch the subject and scores from early trials and try to achieve the best score by encouraging a slow subject to speed up and by reminding a more "careless" subject to be more accurate.

GTA 6: HAND – ARM STEADINESS TEST

INSTRUCTIONS TO SUBJECT

- This test will measure the steadiness of your hand.
- I will strap this small module to your hand. Let me know if you find the strap too tight or loose.
- Extend your arm straight out in front of you and keep it as steady as possible.
- When I start the test, you will hear a single beep. Keep your hand steady until you hear a double beep which will end the test. The duration of each trial is 10 seconds.
- If for some reason you feel fatigue during the trial, please inform me immediately.

INSTRUCTIONS TO EXAMINER:

- Plug the RSM connector into the main HPMM unit and ensure that it is connected properly.
- Make sure you strap the RSM securely to the subject's hand, but do not strap it too tightly. Ensure that the subject is comfortable.
- The subject must extend their forearm with palm facing downward and fingers extended and held together.
- Select READY on the HPMM touch screen only when you are sure the subject has attained correct position. A single beep will signal the start of the measurement and a double beep will signal its end.
- Should the subject experience any fatigue, stop the trial immediately and remove the RSM from the subject's hand. Allow the subject to rest.
- Remember that the RSM is a very delicate device and handle it carefully.

APPENDIX B

HPMM VERSION 4: TEST RESULTS

Table B1: Isometric Strength Test Results

Number	Gender	Age	D. Side	Test Session 1 Grip Strength (N)		Test Session 2 Grip Strength (N)	
				D	N	D	N
1	F	24	R	219	218	217	188
2	M	28	R	287	287	330	295
3	M	27	R	556	538	515	520
4	M	23	R	426	413	319	337
5	M	23	R	477	364	386	375
6	F	23	R	243	237	242	245
7	M	25	R	318	305	305	275
8	M	25	R	316	300	336	278
9	M	26	R	451	464	481	520
10	M	25	R	391	337	457	411
11	F	24	R	339	316	348	338
12	F	24	R	223	206	204	189
13	F	26	R	262	242	332	302
14	M	25	R	469	590	525	576
15	F	25	R	230	218	268	255
16	F	24	R	192	160	211	201
17	F	25	R	230	200	267	229
18	F	24	R	259	236	227	202
19	M	24	R	355	346	491	397
20	F	25	R	288	266	304	296

Table B2: Simple Visual Response Speed Test Results

Number	Gender	Age	D. Side	Test Session 1 Response Speed (resp/s)	Test Session 2 Response Speed (resp/s)
1	F	24	R	5.617	5.631
2	M	28	R	5.383	5.575
3	M	27	R	5.777	5.761
4	M	23	R	5.413	5.180
5	M	23	R	6.137	6.252
6	F	23	R	5.088	5.698
7	M	25	R	5.932	6.526
8	M	25	R	5.848	5.607
9	M	26	R	5.490	5.627
10	M	25	R	4.622	4.518
11	F	24	R	5.407	5.545
12	F	24	R	5.728	6.163
13	F	26	R	4.919	5.016
14	M	25	R	5.552	5.695
15	F	25	R	4.844	4.817
16	F	24	R	5.274	6.176
17	F	25	R	5.348	5.944
18	F	24	R	5.085	5.264
19	M	24	R	5.737	6.013
20	F	25	R	4.545	4.739

Table B3: Finger Tapping Performance Test Results (Test Session 1)

Number	Sex	Age	D. Side	Tapping Speed (taps/s)				Duty Cycle Mean (%)				Duty Cycle S.D. (%)			
				D		N		D		N		D		N	
1	F	24	R	5.3	5.4	4.7	4.4	25.7	33.7	36.5	26.7	5.0	7.1	15.3	12.4
2	M	28	R	5.0	4.9	4.7	3.9	42.5	39.3	37.9	34.3	10.4	12.8	14.7	10.0
3	M	27	R	5.2	5.3	4.5	4.6	31.8	29.3	36.4	38.8	13.2	14.7	13.6	15.5
4	M	23	R	5.3	5.4	4.4	4.6	24.9	31.5	26.9	31.6	7.1	14.8	10.0	4.1
5	M	23	R	5.2	4.9	4.6	4.7	43.0	42.7	35.8	47.5	8.9	13.5	3.3	14.2
6	F	23	R	4.4	4.3	3.8	3.9	48.8	54.6	42.6	47.4	10.0	7.6	13.0	11.9
7	M	25	R	6.0	6.1	5.6	5.3	39.1	41.6	52.1	54.5	6.8	9.3	7.0	3.7
8	M	25	R	6.7	6.7	6.2	5.8	37.7	36.8	34.7	42.5	8.4	7.9	10.0	9.3
9	M	26	R	5.9	5.9	5.3	5.2	32.9	30.3	30.7	30.5	13.6	12.2	13.6	13.2
10	M	25	R	5.7	5.5	5.3	5.1	29.4	29.3	34.4	37.5	14.5	2.8	12.9	8.4
11	F	24	R	5.9	5.6	5.4	5.0	39.4	44.8	51.2	39.3	12.1	8.5	8.4	12.4
12	F	24	R	5.2	5.4	4.7	4.5	38.2	47.8	47.9	42.7	12.2	9.0	14.5	15.2
13	F	26	R	4.5	4.7	4.4	4.2	33.0	34.5	29.4	52.9	8.5	12.5	13.1	11.3
14	M	25	R	5.6	5.3	5.8	5.4	39.6	35.3	39.9	34.3	16.0	8.8	15.3	13.3
15	F	25	R	5.0	5.0	4.4	4.3	34.8	33.3	37.3	39.5	14.0	14.5	14.5	13.9
16	F	24	R	5.0	5.3	4.9	5.0	21.5	32.3	35.8	39.1	10.0	13.7	14.0	10.8
17	F	25	R	4.7	4.3	4.7	4.3	34.1	36.9	42.5	41.0	15.0	2.2	11.7	14.0
18	F	24	R	5.1	5.2	4.7	4.8	24.6	31.2	27.8	30.0	5.8	12.3	6.3	14.8
19	M	24	R	5.6	5.6	5.3	5.0	36.7	43.3	44.1	40.7	10.6	8.9	7.2	10.3
20	F	25	R	5.0	5.1	4.7	4.7	38.6	40.5	31.4	42.3	10.6	10.4	15.8	13.1

Table B4: Finger Tapping Performance Test Results (Test Session 2)

Number	Sex	Age	D. Side	Tapping Speed				Duty Cycle Mean (%)				Duty Cycle S.D. (%)			
				D		N		D		N		D		N	
1	F	24	R	5.0	4.9	4.1	4.1	25.4	21.9	23.0	29.5	8.2	10.1	14.2	14.5
2	M	28	R	5.1	4.9	4.1	4.3	35.2	25.4	25.9	34.6	11.8	8.1	11.1	5.1
3	M	27	R	5.7	4.9	4.9	4.7	29.6	20.5	35.7	33.8	12.1	9.5	12.8	14.5
4	M	23	R	6.0	5.5	5.1	4.6	25.7	25.8	30.2	28.6	13.9	15.3	14.4	6.3
5	M	23	R	5.3	4.8	5.0	4.5	41.4	41.6	33.0	35.7	10.7	5.7	13.7	5.0
6	F	23	R	5.2	5.1	4.5	4.0	54.0	49.1	42.4	44.3	15.2	6.1	9.5	10.6
7	M	25	R	5.8	5.7	5.7	5.6	43.2	41.6	52.8	52.1	13.7	9.3	15.7	15.7
8	M	25	R	6.9	6.9	5.3	5.6	40.9	41.6	51.9	45.1	9.1	7.1	13.3	12.4
9	M	26	R	6.1	5.7	5.2	4.9	29.5	24.1	28.1	34.1	12.8	15.1	14.7	8.4
10	M	25	R	5.9	5.2	5.1	4.6	30.0	26.1	28.5	31.3	13.7	5.6	14.7	7.9
11	F	24	R	5.8	5.5	5.4	5.2	39.6	39.4	24.9	47.1	10.5	15.0	15.5	10.5
12	F	24	R	5.1	4.5	4.4	3.9	42.8	50.2	51.4	40.8	15.3	12.1	11.4	6.3
13	F	26	R	4.4	4.1	4.5	4.4	24.7	24.5	34.9	46.8	12.9	13.0	14.4	11.8
14	M	25	R	5.1	5.3	5.8	5.8	31.1	36.3	37.6	36.0	15.3	14.7	2.0	13.0
15	F	25	R	4.9	4.9	4.5	4.2	40.1	33.3	31.1	41.8	10.7	13.9	4.1	14.1
16	F	24	R	5.3	4.8	5.7	5.4	31.7	32.1	35.2	32.0	5.4	3.3	11.8	5.6
17	F	25	R	4.2	4.8	4.7	4.1	36.3	34.9	34.5	37.3	4.5	15.1	13.0	7.6
18	F	24	R	5.4	5.1	5.0	4.9	33.0	37.2	33.6	32.0	12.4	10.3	15.7	5.4
19	M	24	R	5.8	5.3	5.2	5.0	40.0	34.1	40.8	38.2	9.1	13.2	10.7	10.5
20	F	25	R	5.2	4.8	4.9	4.6	38.7	31.7	34.2	37.8	14.9	9.1	16.0	13.7

Table B5: Upper Extremity Coordination (NMCC) Test Results (Test Session 1)

Number	Sex	Age	D. Side	Movement Speed (cm/s)				Accuracy (%)				NMCC (bits/s)			
				D		N		D		N		D		N	
1	F	24	R	45.72	57.91	42.67	50.29	83	71	71	69	12.93	14.01	10.32	11.83
2	M	28	R	38.10	44.19	41.14	36.57	80	79	59	62	10.39	11.90	8.05	7.73
3	M	27	R	38.10	32.00	30.48	41.14	96	85	95	74	12.47	9.27	9.87	10.38
4	M	23	R	53.34	45.72	47.24	44.19	62	66	74	89	11.27	10.06	11.92	13.18
5	M	23	R	41.14	45.72	36.57	33.52	85	93	79	86	11.92	14.49	9.62	9.83
6	F	23	R	45.72	48.76	35.05	32.00	80	78	60	61	12.47	12.74	6.94	6.65
7	M	25	R	41.14	51.81	30.48	36.57	85	82	85	87	11.92	14.48	8.83	10.85
8	M	25	R	39.62	32.00	47.24	32.00	88	90	64	76	11.66	9.82	10.30	8.29
9	M	26	R	28.95	25.90	33.52	33.52	89	82	81	81	8.78	7.24	9.25	9.25
10	M	25	R	60.96	42.67	45.72	39.62	52	71	60	73	10.80	10.32	9.35	9.64
11	F	24	R	53.34	45.72	41.14	39.62	71	73	74	73	12.91	11.37	10.38	9.64
12	F	24	R	41.14	32.00	42.67	32.00	77	85	71	85	10.80	9.27	10.32	9.27
13	F	26	R	35.05	41.14	27.43	25.90	86	88	88	88	10.27	12.34	8.23	7.77
14	M	25	R	42.67	39.62	41.14	38.10	71	76	70	68	10.32	10.26	9.82	8.83
15	F	25	R	32.00	32.00	36.57	32.00	95	95	87	85	10.36	10.36	10.85	9.27
16	F	24	R	50.29	56.38	45.72	44.19	81	75	76	65	13.88	14.42	11.62	9.79
17	F	25	R	38.10	35.05	33.52	30.48	96	95	95	95	12.47	11.35	10.86	9.87
18	F	24	R	57.91	42.67	30.48	35.05	63	89	90	91	12.43	12.94	9.35	10.87
19	M	24	R	28.95	28.95	28.95	35.05	94	89	78	65	9.27	8.78	7.69	7.76
20	F	25	R	39.62	42.67	38.10	33.52	92	82	76	81	12.42	11.93	9.65	9.25

Table B6: Upper Extremity Coordination (NMCC) Test Results (Test Session 2)

Number	Sex	Age	D. Side	Movement Speed (cm/s)				Accuracy (%)				NMCC (bits/s)			
				D		N		D		N		D		N	
1	F	24	R	41.14	47.24	50.29	47.24	85	87	78	77	11.92	14.01	13.37	12.40
2	M	28	R	42.67	44.19	32.00	27.43	75	75	80	83	10.91	11.30	8.72	7.76
3	M	27	R	41.14	33.52	28.95	36.57	85	72	94	79	11.92	8.23	9.27	9.62
4	M	23	R	45.72	44.19	35.05	30.48	83	93	86	90	12.93	14.01	10.27	9.35
5	M	23	R	50.29	42.67	36.57	27.43	84	82	79	83	14.40	11.93	9.62	7.76
6	F	23	R	47.24	45.72	38.10	32.00	70	83	72	71	11.27	12.93	9.35	7.74
7	M	25	R	44.19	41.14	38.10	24.38	72	77	68	87	10.85	10.80	8.83	7.23
8	M	25	R	54.86	62.48	47.24	44.19	91	85	77	86	17.02	18.11	12.40	12.95
9	M	26	R	41.14	42.67	36.57	38.10	74	85	79	76	10.38	12.36	9.62	9.65
10	M	25	R	41.14	47.24	44.19	38.10	81	87	62	64	11.36	14.01	9.34	8.31
11	F	24	R	47.24	47.24	33.52	38.10	87	93	81	92	14.01	14.75	9.25	11.95
12	F	24	R	41.14	38.10	33.52	33.52	85	84	68	68	11.92	10.91	7.77	7.77
13	F	26	R	42.67	25.90	36.57	36.57	78	94	70	83	11.34	8.30	8.50	10.34
14	M	25	R	47.24	48.76	39.62	38.10	90	71	84	80	14.49	11.80	11.34	10.39
15	F	25	R	47.24	33.52	36.57	33.52	80	95	62	95	12.88	10.86	7.73	10.86
16	F	24	R	54.86	56.38	44.19	38.10	86	78	79	76	16.08	14.99	11.90	9.65
17	F	25	R	35.05	39.62	28.95	36.57	91	96	78	75	10.87	12.74	7.69	9.35
18	F	24	R	51.81	56.38	36.57	45.72	85	81	75	63	15.01	15.57	9.35	9.82
19	M	24	R	28.95	30.48	25.90	25.90	94	95	82	82	9.27	9.87	7.24	7.24
20	F	25	R	38.10	41.14	35.05	39.62	88	85	86	76	11.20	11.92	10.27	10.26

Table B7: Hand-Arm Steadiness Test Results – Translational Steadiness – X Axis (Test Session 1)

Number	Sex	Age	D. Side	Translational Acceleration Based Steadiness - X axis (1/g)					
				D			N		
1	F	24	R	55.970	56.320	63.459	60.074	64.365	68.266
2	M	28	R	69.316	72.670	70.400	63.909	64.365	66.258
3	M	27	R	58.514	48.709	48.709	51.492	53.007	57.032
4	M	23	R	79.745	77.018	77.018	80.457	85.820	82.671
5	M	23	R	59.676	59.676	61.720	61.720	64.828	67.247
6	F	23	R	40.590	41.147	35.617	37.862	40.774	53.638
7	M	25	R	43.743	48.447	49.241	54.946	51.200	54.946
8	M	25	R	40.960	46.933	47.179	51.492	47.678	46.933
9	M	26	R	85.011	81.181	69.316	67.247	79.045	72.089
10	M	25	R	58.136	58.136	52.087	52.087	55.624	56.320
11	F	24	R	63.459	62.146	55.970	59.284	65.775	62.577
12	F	24	R	62.577	62.146	62.146	67.247	61.300	67.247
13	F	26	R	69.316	60.074	68.266	65.775	67.753	66.258
14	M	25	R	75.724	69.854	75.093	58.896	68.266	65.775
15	F	25	R	51.492	52.697	59.284	62.146	63.015	61.720
16	F	24	R	68.266	77.682	77.682	74.472	73.261	70.954
17	F	25	R	43.957	39.350	42.306	46.211	46.690	48.973
18	F	24	R	68.787	54.613	62.577	70.954	73.862	73.261
19	M	24	R	64.365	64.828	80.457	63.909	58.896	63.909
20	F	25	R	50.910	74.472	69.316	66.258	69.316	63.459

Table B8: Hand-Arm Steadiness Test Results – Translational Steadiness – Y Axis (Test Session 1)

Number	Sex	Age	D. Side	Translational Acceleration Based Steadiness - Y axis (1/g)					
				D			N		
1	F	24	R	67.753	70.400	82.671	78.358	84.216	79.045
2	M	28	R	87.487	92.898	95.863	81.181	84.216	88.345
3	M	27	R	79.745	64.828	61.300	61.720	77.018	78.358
4	M	23	R	109.892	89.219	114.065	114.065	115.528	114.065
5	M	23	R	89.219	80.457	86.646	85.820	93.866	88.345
6	F	23	R	53.959	59.676	45.975	53.007	52.087	72.670
7	M	25	R	57.032	58.514	64.365	71.517	72.670	71.517
8	M	25	R	68.266	64.828	59.284	55.283	62.146	58.136
9	M	26	R	111.249	115.528	85.820	88.345	91.022	94.854
10	M	25	R	72.670	70.954	61.300	68.787	64.365	73.261
11	F	24	R	76.366	72.670	79.045	79.745	79.745	75.093
12	F	24	R	85.011	76.366	80.457	81.181	75.724	77.682
13	F	26	R	95.863	75.093	85.011	84.216	85.820	81.181
14	M	25	R	88.345	93.866	106.014	77.018	96.894	92.898
15	F	25	R	68.266	68.787	77.018	75.093	81.181	75.093
16	F	24	R	83.437	108.568	96.894	100.124	92.898	91.022
17	F	25	R	59.284	52.697	59.284	61.720	67.753	68.266
18	F	24	R	85.820	63.015	79.745	89.219	95.863	97.947
19	M	24	R	93.866	91.951	123.441	85.011	79.745	81.181
20	F	25	R	70.400	102.400	96.894	81.920	100.124	84.216

Table B9: Hand-Arm Steadiness Test Results – Rotational Steadiness – X Axis (Test Session 1)

Number	Sex	Age	D. Side	Rotational Rate Based Steadiness - X axis (s/deg)					
				D			N		
1	F	24	R	0.91	0.91	1.00	1.00	1.11	1.00
2	M	28	R	1.25	1.43	1.43	1.25	1.11	1.43
3	M	27	R	1.00	1.11	1.11	0.91	1.00	1.00
4	M	23	R	1.43	1.25	1.67	2.00	2.00	2.00
5	M	23	R	1.11	1.11	1.00	1.11	1.25	1.25
6	F	23	R	0.91	0.77	0.71	0.91	0.91	0.83
7	M	25	R	1.25	1.11	1.25	1.43	1.25	1.43
8	M	25	R	0.67	0.77	0.63	0.63	0.91	0.83
9	M	26	R	1.43	1.43	1.25	1.43	1.25	1.25
10	M	25	R	0.83	0.83	0.63	0.83	0.63	0.71
11	F	24	R	1.11	0.77	0.91	0.83	1.11	0.91
12	F	24	R	1.67	1.43	1.43	1.43	1.11	1.11
13	F	26	R	1.00	0.67	0.83	0.71	0.83	0.71
14	M	25	R	0.67	0.71	1.25	0.83	1.00	1.11
15	F	25	R	1.67	1.43	1.43	1.25	1.25	1.11
16	F	24	R	1.25	1.11	1.25	1.43	1.11	1.11
17	F	25	R	1.43	1.67	1.67	1.67	2.00	2.00
18	F	24	R	0.77	0.63	0.77	0.83	1.00	1.00
19	M	24	R	1.43	1.43	1.43	1.11	1.00	1.00
20	F	25	R	1.25	1.11	1.67	1.11	1.25	1.67

Table B10: Hand-Arm Steadiness Test Results – Rotational Steadiness – Z Axis (Test Session 1)

Number	Sex	Age	D. Side	Rotational Rate Based Steadiness - Z axis (s/deg)					
				D			N		
1	F	24	R	0.63	0.67	0.77	0.71	0.71	0.71
2	M	28	R	0.91	0.83	1.00	0.67	0.63	0.71
3	M	27	R	0.77	0.77	0.71	0.67	0.77	0.63
4	M	23	R	1.67	1.43	1.25	1.67	1.67	1.43
5	M	23	R	0.42	0.43	0.37	0.50	0.56	0.59
6	F	23	R	0.67	0.50	0.50	0.34	0.32	0.45
7	M	25	R	0.77	0.83	0.77	0.83	0.77	0.83
8	M	25	R	0.21	0.25	0.36	0.29	0.29	0.40
9	M	26	R	1.00	0.91	0.83	0.83	0.83	0.77
10	M	25	R	0.48	0.34	0.36	0.40	0.38	0.38
11	F	24	R	1.00	0.77	0.56	0.56	0.83	0.56
12	F	24	R	0.83	0.83	0.91	0.77	0.71	0.83
13	F	26	R	0.67	0.50	0.67	0.50	0.50	0.56
14	M	25	R	1.00	0.83	1.43	0.67	0.91	0.91
15	F	25	R	1.67	1.25	1.43	0.91	1.43	1.43
16	F	24	R	0.71	0.67	0.77	0.67	0.56	0.63
17	F	25	R	0.91	0.83	0.91	0.83	0.91	0.91
18	F	24	R	0.83	0.53	0.63	0.91	1.00	0.91
19	M	24	R	0.71	0.67	0.77	0.56	0.48	0.63
20	F	25	R	0.67	0.77	0.83	0.59	0.71	0.83

Table B11: Hand-Arm Steadiness Test Results – Translational Steadiness – X Axis (Test Session 2)

Number	Sex	Age	D. Side	Translational Acceleration Based Steadiness - X axis (1/g)					
				D			N		
1	F	24	R	71.517	75.093	68.266	69.854	71.517	69.854
2	M	28	R	67.753	61.300	67.247	60.886	60.886	65.775
3	M	27	R	53.959	60.886	48.973	60.886	63.909	68.787
4	M	23	R	76.366	73.261	75.093	76.366	79.045	81.181
5	M	23	R	70.954	68.787	70.954	70.400	66.258	62.146
6	F	23	R	53.638	40.774	48.188	51.200	45.975	41.912
7	M	25	R	60.074	62.146	70.400	65.298	70.400	64.365
8	M	25	R	40.408	52.697	50.341	53.638	50.910	48.709
9	M	26	R	77.018	68.266	69.316	69.854	69.316	67.753
10	M	25	R	60.074	66.749	67.753	61.300	60.886	62.577
11	F	24	R	68.787	67.247	67.753	72.089	66.258	68.266
12	F	24	R	79.045	77.018	65.298	67.247	69.316	70.954
13	F	26	R	69.316	55.283	50.910	62.146	66.258	68.266
14	M	25	R	77.682	74.472	73.261	63.459	54.284	65.775
15	F	25	R	77.018	82.671	77.018	77.018	84.216	81.920
16	F	24	R	81.920	85.011	85.011	78.358	81.181	88.345
17	F	25	R	80.457	80.457	82.671	80.457	75.724	80.457
18	F	24	R	69.316	73.862	75.724	73.261	67.753	70.400
19	M	24	R	75.093	70.954	75.093	63.909	70.400	68.787
20	F	25	R	73.261	68.787	66.749	73.862	82.671	76.366

Table B12: Hand-Arm Steadiness Test Results – Translational Steadiness – Y Axis (Test Session 2)

Number	Sex	Age	D. Side	Translational Acceleration Based Steadiness - Y axis (1/g)					
				D			N		
1	F	24	R	88.345	100.124	95.863	95.863	100.124	90.112
2	M	28	R	90.112	76.366	86.646	85.011	82.671	85.820
3	M	27	R	74.472	81.181	66.258	85.011	91.951	91.951
4	M	23	R	100.124	107.276	109.892	117.028	121.772	114.065
5	M	23	R	91.951	91.951	92.898	92.898	90.112	94.854
6	F	23	R	62.577	54.613	63.459	67.753	66.749	66.258
7	M	25	R	75.724	84.216	102.400	79.745	85.011	87.487
8	M	25	R	50.910	58.514	60.477	69.854	61.720	62.146
9	M	26	R	104.781	89.219	85.820	86.646	96.894	96.894
10	M	25	R	94.854	92.898	106.014	77.018	65.775	74.472
11	F	24	R	100.124	91.022	90.112	93.866	88.345	85.820
12	F	24	R	107.276	88.345	72.670	77.682	77.018	70.954
13	F	26	R	87.487	66.258	68.266	63.909	70.400	84.216
14	M	25	R	93.866	93.866	94.854	80.457	69.316	86.646
15	F	25	R	95.863	91.951	91.022	99.024	91.951	91.022
16	F	24	R	101.249	123.441	115.528	118.568	114.065	121.772
17	F	25	R	107.276	103.577	114.065	106.014	101.249	109.892
18	F	24	R	88.345	96.894	99.024	101.249	94.854	89.219
19	M	24	R	93.866	92.898	104.781	90.112	92.898	87.487
20	F	25	R	107.276	101.249	95.863	101.249	114.065	107.276

Table B13: Hand-Arm Steadiness Test Results – Rotational Steadiness – X Axis (Test Session 2)

Number	Sex	Age	D. Side	Rotational Rate Based Steadiness - X axis (s/deg)					
				D			N		
1	F	24	R	0.83	1.11	0.91	1.25	1.25	1.25
2	M	28	R	1.25	1.11	1.25	1.43	1.25	1.11
3	M	27	R	0.91	1.25	1.00	0.91	0.83	1.00
4	M	23	R	1.67	1.67	2.00	2.00	2.50	2.50
5	M	23	R	1.25	1.25	1.25	1.11	1.11	1.11
6	F	23	R	0.77	0.77	0.77	0.77	0.77	0.59
7	M	25	R	1.11	1.43	1.67	1.00	1.11	1.11
8	M	25	R	0.67	0.63	0.63	0.83	0.77	0.83
9	M	26	R	1.43	1.43	1.25	1.43	1.67	1.67
10	M	25	R	0.83	0.83	1.00	0.77	0.56	0.71
11	F	24	R	1.43	1.11	1.11	1.25	1.11	1.11
12	F	24	R	1.11	1.25	0.83	1.25	1.00	0.83
13	F	26	R	1.00	0.71	0.67	0.63	0.67	0.83
14	M	25	R	1.11	0.91	0.91	0.71	0.53	0.71
15	F	25	R	1.25	1.43	1.43	1.43	1.43	1.25
16	F	24	R	1.25	1.43	1.25	1.43	1.67	1.43
17	F	25	R	1.67	1.43	1.67	1.43	1.43	1.67
18	F	24	R	1.11	1.11	1.11	1.43	1.11	1.00
19	M	24	R	1.25	1.25	1.25	1.00	1.11	1.11
20	F	25	R	1.25	1.00	1.00	1.25	1.43	1.11

Table B14: Hand-Arm Steadiness Test Results – Rotational Steadiness – Z Axis (Test Session 2)

Number	Sex	Age	D. Side	Rotational Rate Based Steadiness - X axis (s/deg)					
				D			N		
1	F	24	R	0.50	0.71	0.83	0.83	0.91	0.91
2	M	28	R	0.91	0.91	0.91	0.71	0.67	0.63
3	M	27	R	0.56	0.83	0.67	0.67	0.56	0.83
4	M	23	R	1.67	1.43	1.67	1.67	2.00	2.50
5	M	23	R	0.53	0.56	0.67	0.50	0.53	0.53
6	F	23	R	0.63	0.63	0.67	0.34	0.32	0.30
7	M	25	R	0.83	0.91	0.91	0.71	0.71	0.67
8	M	25	R	0.29	0.33	0.27	0.32	0.26	0.24
9	M	26	R	1.00	0.83	0.91	0.91	0.83	0.71
10	M	25	R	0.34	0.53	0.48	0.43	0.48	0.56
11	F	24	R	0.91	0.67	0.83	1.00	0.83	0.91
12	F	24	R	0.71	0.67	0.77	0.59	0.71	0.67
13	F	26	R	0.77	0.56	0.67	0.56	0.71	0.83
14	M	25	R	1.11	1.25	0.83	0.71	0.50	0.63
15	F	25	R	1.25	1.43	1.43	1.11	1.43	1.43
16	F	24	R	1.11	1.11	1.00	0.77	1.11	1.00
17	F	25	R	1.25	1.43	1.67	1.25	1.11	1.43
18	F	24	R	0.91	1.11	0.91	1.25	1.11	0.91
19	M	24	R	0.71	0.77	0.83	0.59	0.77	0.77
20	F	25	R	0.71	0.53	0.50	0.71	0.83	0.71

Table B15: 4-DOF Steadiness (Test Session 1)

Number	Sex	Age	D. Side	4-DOF Steadiness (SUs)[1]					
				Dominant Side			Non-dominant Side		
1	F	24	R	2155	2403	4036	3362	4302	3854
2	M	28	R	6891	8037	9641	4323	3764	5973
3	M	27	R	3589	2699	2370	1926	3140	2793
4	M	23	R	20865	12270	18302	30591	33049	26942
5	M	23	R	2465	2319	1981	2943	4226	4368
6	F	23	R	1327	944	585	629	623	1476
7	M	25	R	2399	2625	3047	4678	3578	4678
8	M	25	R	388	585	624	508	792	909
9	M	26	R	13511	12180	6197	7073	7495	6575
10	M	25	R	1676	1185	713	1194	861	1134
11	F	24	R	5385	2672	2234	2189	4857	2373
12	F	24	R	7389	5650	6494	5999	3684	4837
13	F	26	R	4430	1504	3224	1978	2423	2134
14	M	25	R	4460	3903	14216	2520	6013	6172
15	F	25	R	9764	6473	9318	5303	9135	7357
16	F	24	R	5086	6247	7237	7101	4201	4485
17	F	25	R	3384	2880	3800	3961	5752	6079
18	F	24	R	3784	1132	2399	4796	7081	6523
19	M	24	R	6165	5677	10914	3354	2237	3243
20	F	25	R	2987	6518	9328	3548	6197	7423

[1]SU (Steadinesss Unit) is s^2/deg^2g^2

Table B16: 4-DOF Steadiness (Test Session 2)

Number	Sex	Age	D. Side	4-DOF Steadiness (SUs)[1]					
				Dominant Side			Non-dominant Side		
1	F	24	R	2633	5967	4958	6975	8137	7153
2	M	28	R	6938	4729	6621	5282	4195	3920
3	M	27	R	2030	5149	2163	3137	2721	5271
4	M	23	R	21239	18712	27507	29790	48127	57874
5	M	23	R	4292	4392	5493	3633	3492	3447
6	F	23	R	1614	1071	1568	920	761	495
7	M	25	R	4212	6797	10923	3719	4750	4171
8	M	25	R	392	642	514	1007	636	615
9	M	26	R	11529	7251	6760	7860	9328	7815
10	M	25	R	1637	2720	3420	1579	1059	1849
11	F	24	R	8944	4534	5653	8458	5420	5918
12	F	24	R	6730	5670	3042	3841	3813	2797
13	F	26	R	4665	1454	1545	1379	2221	3992
14	M	25	R	9002	7944	5264	2605	990	2544
15	F	25	R	11536	15514	14307	12106	15804	13315
16	F	24	R	11520	16657	12276	10210	17148	15368
17	F	25	R	17981	17007	26194	15231	12170	21051
18	F	24	R	6186	8836	7574	13246	7934	5710
19	M	24	R	6293	6338	8196	3388	5590	5144
20	F	25	R	7017	3666	3199	6677	11226	6502

[1]SU (Steadinesss Unit) is s^2/deg^2g^2

APPENDIX C

INSTITUTIONAL REVIEW BOARD DOCUMENTS

THE UNIVERSITY OF TEXAS AT ARLINGTON

OFFICE OF RESEARCH COMPLIANCE

Date: July 11, 2005

To: Dr. George Kondraske
Electrical Engineering
19180

Re: **Protocol 05.395** *Investigation of a Portable Performance Measurement System for Neurological Screening in Clinics – Part 1*

The Institutional Review Board (IRB) has reviewed and approved this research protocol under an expedited review in accordance with Title 45 CFR 46.110. Continuing review is scheduled for one year from the above approval date.

The Office for Human Research Protections (OHRP) requires you to submit annual and final reports for review and approval by the IRB. The annual report must be on file with the IRB before the anniversary date of your initial approval. OHRP does not allow for a grace period on the continual review requirement. If the annual report is not received by the IRB by the anniversary date, the IRB will be forced to terminate the approval of your protocol and if your study is federally funded, the IRB will have to report the termination to OHRP as required by Title 45 CFR 46.103(b) 5.

If you require modifications to this proposal in the method of use of human subjects in this study, change in the Principal Investigator (PI) or Co- Investigator(s), or any change in the subject pool, you are required to obtain prior approval from the IRB before implementing the modification as required by Title 45 CFR 46.103(b) 4iii.

The IRB approved consent form that is stamped by the IRB with the expiration date of the approval must be used for all informed consent procedures on all human subjects in this study. The signed consent forms must be under lock and key on UTA campus for the duration of the study plus three years. These consent forms are subject to inspection during this time period by the IRB, Research Compliance staff and / or federal agents.

All investigators listed in this protocol must have documented Human Subjects Involved in Research (Tier II) training on file with the Office of Research Compliance. Please call the Office of Research Compliance if you have not taken the training course within the last year.

If you have any questions related to this research or to the IRB, you may contact me at (817) 272-4840 or the Office of Research Compliance at (817) 272-3723.

Sincerely,

Dr. Jennifer Gray

Dr. Jennifer Gray
Assistant Professor
IRB Chair

BOX 19188 202 E. BORDER, SUITE 201 ARLINGTON, TEXAS 76019-0188 T 817.272.3723 F 817.303.9187

Figure C1 Institutional Review Board Approval Letter

Subject #: ______________ U TA IRB Protocol # 05.395

THE UNIVERSITY OF TEXAS AT ARLINGTON

PARTICIPATION EXPLANATION AND CONSENT FORM

PROJECT TITLE: Investigation of a Portable Performance Measurement System for Neurological Screening in Clinics – Part I

INVESTIGATORS: George V. Kondraske, Ph.D., Professor, Electrical and Biomedical Engineering; Rahul Mulukutla (Graduate Student, EE Department)

TELEPHONE NUMBER: (817) 272-3454, (817)-272-2335

BACKGROUND INFORMATION:

I have been asked to participate in a research study that will investigate the validity and repeatability of measures obtained using prototypes of components of a portable performance measurement instrument. This tool is called the "Human Performance Multi Meter" (HPMM) and the investigation pertains to its latest version. This instrument may ultimately combine several instruments that are currently only available in large, laboratory settings, into a single, small unit. It has the potential to allow medical practitioners (e.g., neurologists) and others to rapidly assess many aspects of human performance, including strength, speed of movements and tremor measurements, without having to refer the patient to a specialized laboratory.

The current study seeks to evaluate if the instrument provides measurements that are comparable to those obtained with other laboratory-based instruments.

PROCEDURES:

If I agree to participate in this study, I will be involved in one testing session lasting approximately one hour. Tests will be performed at the Human Performance Institute at the University of Texas at Arlington

I will undergo a series of performance capacity tests in order to determine selected "performance resource capacities". These tests involve simple motions of the fingers and arms in response to visual and auditory signals. Grip strength will also be tested. The series of tests will be repeated twice during the session.

RISKS THAT MAY OCCUR DURING THE STUDY:

There are few potential risks involved in this study. During the testing, I may experience some fatigue or possibly some confusion.

The possible risks involved in this study are relatively slight. The processes and protocols described in the proposal are the only way in which the necessary information can be obtained.

JUL 11 2005

APPROVED BY THE UTA-IRB
The IRB approval for this consent document will expire on

JUL 10 2006

1

Figure C2 Participation Explanation and Consent Form – Page 1

BENEFITS FOR YOUR PARTICIPATION:
By participating in this study, I will be assisting in the evaluation of a new tool that may benefit many others in the future. It is expected to lay the groundwork for future work that may prove to be valuable for diagnosis and evaluation of the effectiveness of new drugs and therapies. I will also learn about some aspects of human performance and performance measurement.

AVAILIBILITY OF COMPENSATION AND MEDICAL TREATMENT FOR PHYSICAL INJURY:
The investigators will make every effort to prevent physical injury that could result from this research. If I am injured, the research protocol does not require the payment of financial compensation to me from the investigator or the University of Texas at Arlington. Medical treatment for physical injuries is not available from the researchers as part of the research protocol. The University of Texas at Arlington Heath Services will provide medical treatment, should an acute condition arise from my participation in this study. I will be financially responsible for any emergency medical care I receive.

CONFIDENTIALITY:
I have the right to privacy, and all information that is obtained in connection with this study and that can be identified with me will remain confidential as far as possible within state and federal law. Everything the investigators learn about me in the study will be confidential. The results of this study may be published in the medical literature or for teaching purposes; no names will be used. No photographs, audio- or videotapes will be used.

Records will be kept regarding my participation in the study and will be made available for review only as required by the Food and Drug Administration.

REQUEST FOR MORE INFORMATION:
If I have any questions about the study, I should contact:

George Kondraske (817) 272-3454

If I need to report any adverse event or problem concerning my participation in the study, I should contact:

George Kondraske (817) 272-3454

If I have any questions about my rights as a research subject I should contact:

UTA Office of Research Compliance (817) 272-3723

REFUSAL OR WITHDRAWL OF PARTICIPATION:
My participation is voluntary and I may refuse to participate, or may withdraw consent and discontinue participation in the study at any time without prejudice to my present enrolment or employment at the University of Texas at Arlington. Either George Kondraske or Rahul Mulukutla may terminate my participation in this study after explaining the reasons for doing so.

I will be given a copy of this form to keep.

JUL 1 1 2005

APPROVED BY THE UTA-IRB
The IRB approval for this consent document will expire on

JUL 1 0 2006

2

Figure C3 Participation Explanation and Consent Form – Page 2

CONSENT TO PARTICIPATE:

I am making a decision whether or not to participate in this study. I should not sign this consent form until I have read (or have been read) and understand the information presented in the previous pages, and until all my questions about the experimental project and the study procedures I will undergo have been answered to my satisfaction. My signature indicates that I have made an informed decision to participate.

I have explained to ______________________________ the purpose of the experimental project, the procedures required, and the possible risks and benefits to the best of my ability.

______________________________ ____________

Signature of investigator Date

______________________________ ____________

Signature of person obtaining consent Date

______________________________- has explained to me the purpose of the experimental project. I have read (or been read) and understand this consent form. I have been given an opportunity to ask questions regarding the experimental project and the study procedures I will undergo, and I believe that I have sufficient information to give this informed consent. Alternatives to my participation in the study have been discussed. To the best of my knowledge, I am not participating in any other medical research. Therefore, I agree to give my consent to participate as a subject in this research project.

______________________________ ____________

Signature of subject Date

JUL 1 1 2005

APPROVED BY THE UTA-IRB
The IRB approval for this consent
document will expire on

JUL 1 0 2006

3

Figure C4 Participation Explanation and Consent Form – Page 3

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BIOGRAPHICAL INFORMATION

The author was born in Pune, India in the year 1981. He received his Bachelor of Engineering degree in Telecommunications Engineering from Visveswaraiah Technological University, India in the year 2003 and his Master of Science degree in Electrical Engineering from the University of Texas at Arlington in the year 2005.