Markerless Analysis of Upper Extremity Kinematics during Standardized Pediatric Assessment

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MARKERLESS ANALYSIS OF UPPER EXTREMITY KINEMATICS DURING
STANDARDIZED PEDIATRIC ASSESSMENT

by

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ABSTRACT

MARKERLESS ANALYSIS OF UPPER EXTREMITY KINEMATICS DURING
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Children with hemiplegic cerebral palsy experience reduced motor performance in the affected upper extremity and are typically evaluated based on degree of functional impairment using activity-based assessments such as the Shriners Hospitals for Children Upper Extremity Evaluation (SHUEE), a validated clinical measure, to describe performance prior to and following rehabilitative or surgical interventions. Evaluations rely on subjective therapist scoring techniques and lack sensitivity to detect change. Objective clinical motion analysis systems are an available but time-consuming and cost-intensive alternative, requiring uncomfortable application of markers to the patient. There is currently no available markerless, low-cost system that quantitatively assesses upper extremity kinematics to improve sensitivity of evaluation during standardized task performance.

A motion analysis system was developed, using Microsoft Kinect hardware to track motion during broad arm and subtle hand and finger movements. Algorithms detected and recorded skeletal position and calculated angular kinematics. Lab-developed articulating hand model and elbow fixation devices were used to evaluate accuracy, intra-trial, and inter-trial reliability of the Kinect platform. Results of technical evaluation indicate reasonably accurate detection and differentiation between hand and arm positions.

Twelve typically-developing adolescent subjects were tested to characterize and evaluate performance scores obtained from the SHUEE and Kinect motion analysis system. Feasibility of the platform was determined in terms of kinematics and as an enhancement of quantitative kinematic reporting to the SHUEE, and a population mean of typically developing subject kinematics obtained for future development of performance scoring algorithms. The system was observed to be easily operable and clinically effective in subject testing.

The Kinect motion analysis platform developed to quantify upper extremity motion during standardized tasks is a low-cost, portable, accurate, and reliable system in kinematic reporting, and has demonstrated quality of results in both technical evaluation of the system and a study of its applicability to standardized task-based evaluation, but has hardware and software limitations which will be resolved in future improvements of the system. The SHUEE benefits from improved quantitative data, and the Kinect system provides enhanced sensitivity in clinical upper extremity analysis for children with hemiplegic cerebral palsy.

ACKNOWLEDGMENTS

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CHAPTER 1: BACKGROUND AND LITERATURE REVIEW

I. INTRODUCTION

Children with hemiplegic cerebral palsy (HCP) typically present with motor impairments in the affected upper extremity (UE) due to neurological disturbance of normal brain function. Therapists typically evaluate the extent of remaining movement capabilities in affected limbs using clinical evaluations or clinical motion analysis technologies, with each method having distinct, important benefits and limitations in terms of quantifiable accuracy and clinical ease of use. Quantifying UE mobility in patients with HCP with either method allows clinicians to characterize impairments associated with the condition and ongoing response to rehabilitative or surgical interventions for patients. Numerous clinical evaluation protocols exist to quantify UE performance, but many rely on subjective scoring by trained therapists [1]. While valid clinical protocols, these evaluations have the potential for a lack of sensitivity to detect change following interventions, causing reduced clinical confidence in determining efficacy of rehabilitation procedures and surgical intervention planning.

The Shriners Hospitals for Children Upper Extremity Evaluation (SHUEE) is a validated [2] clinical test of arm and hand function in children aged 3 to 18 with UE orthopedic impairments resulting from HCP, employing therapist-directed tasks designed to approximate activities of daily living. After the tasks are completed, a therapist views a video recording of the session and subjectively scores each task based on established ordinal scales, then calculates the final overall performance scores [2]. Alternatively, clinical motion analysis systems such as the Vicon system can precisely and reliably quantify upper-extremity motion in terms of angular kinematics, thus eliminating the potential for observer bias or subjectivity while increasing sensitivity in results, but require expensive equipment in a permanent laboratory setting along with markers to be placed on the patient in specific anatomical locations to detect motion [3].

The Microsoft Kinect sensor is a commercially available, low-cost video game system accessory that uses depth imaging data to determine position of body segments and interpolate skeletal position. It contains a pair of infrared depth sensors and a standard RGB camera which allow three-dimensional object detection [4]. Algorithms allow the software to locate and track prominent skeletal features, such as joint centers, in real time based on a surface map of the body, thus allowing software to achieve markerless skeletal tracking. The Kinect has many advantages over traditional motion analysis systems, including significantly lower cost, higher portability, and markerless operation, while maintaining reasonable accuracy. In order to enhance the SHUEE, both in terms of therapist ease of use and sensitivity of results, software was developed for the Kinect to track and record body motion, substantially enhancing clinical evaluations by including objective kinematic data in the otherwise subjectively-scored evaluation without requiring the undue complexity of clinical lab-based motion analysis.

II. CEREBRAL PALSY

Hemiplegic cerebral palsy (HCP) is a common developmental movement disorder, affecting 3 to 4 people per 1000 in the United States [34], typically first documented at a very young age and with symptoms persisting into adulthood. HCP is characterized by neurological disturbance of developmental brain function in children, which may be attributed to injury, abnormal development, infection, inflammation, or vascular injury of the brain, and is generally recognized through one-sided motor impairment in the case of hemiplegia [35]. Specific underlying causes and mechanisms of brain disorder in cerebral palsy are as yet undetermined in current medical science, and there is no established, effective cure for the disorder, but rather a broad variety of rehabilitative and surgical interventions designed to gradually improve functional capabilities in affected patients. Functional impairments in children with HCP can range from relatively minor – even undetectable – to severely debilitating, and cerebral palsy is considered to be a lifelong disorder for those it affects.

A. SENSORIMOTOR IMPAIRMENT

Sensorimotor impairment occurs through multiple key mechanisms relevant to the UE. In patients with HCP, motor impairments include reduced muscle strength and hypertonicity [35], including reduced velocity and longer movement duration [28,30]. Additionally, joint rigidity [36] is observed to include reduction in active supination range of motion [3,13,28], reduced shoulder flexion [28], and reduced elbow extension [28]. Further limitations include reduced precision grip control [32], increased trunk movement during arm reaching tasks [28], and less-linear hand trajectories [30]. A survey of current research knowledge of important sensorimotor impairments in children with HCP as relevant to UE activity of daily living (ADL) performance is presented in Table 1.1.

Table 1.1. Sensory and Motor Impairments in Hemiplegic Cerebral Palsy

Author(s)	Focus	Methods	Key Findings
Klotz et al. [3]	UE range of motion in adults with HCP	n=15 adults with HCP; performed ADL while UE motion capture performed	Significant reduced ROM in elbow, shoulder, and trunk; most pronounced reduction in forearm pronation/supination – with affected subjects 45° lower ROM
Braendvik et al. [13]	Relates HCP UE impairments with activity performance	n=23 children with CP; measured strength, tone, ROM, and force control	Limitations in active supination range and force control cause significant reduction in activity performance
Mackey et al. [28]	Kinematic analysis of UE	n=10 children with HCP & n=10 control; 3D UE motion analysis; hand-to-head, hand-to-mouth, and reach tasks	HCP: lower velocity, less supination, less shoulder flexion, increased trunk compensation, reduced elbow extension
Jaspers et al. [30]	Kinematic analysis of UE	n=20 children with HCP & n=20 control; 3D UE motion analysis; reach, reach-to-grasp, and gross motor tasks	HCP: longer movement duration, lower velocity, less-linear hand trajectory, increased trunk compensation, changes in multi-joint coordination

Author(s)	Focus	Methods	Key Findings
Bleyenheuft & Gordon [32]	UE functional deficits in HCP	Clinical review of sensorimotor studies of UE in HCP	HCP: Sensory deficits common, reduced precision grip control causes difficulties in ADL performance
Deon & Gaebler-Spira [36]	Movement disorder assessment in CP	Clinical review	HCP: spasticity, hypertonia, and joint rigidity common sensorimotor effects

Sensory impairments associated with HCP have a negative effect on developing and using more mature movement patterns during functional activities. These impairments may reduce the capability of individuals with HCP to use predictive motor control strategies based on sensory feedback [32], and may modify their perception of object gripping. These deficiencies result in patients with HCP having reduced upper extremity performance of gross and fine motor ADL [22,28] reducing their participation in recreational or social activities [11,37].

B. INTERVENTION

Patients with upper extremity involvement resulting from HCP receive two primary methods of intervention: rehabilitative physical/occupational therapy, pharmaceutical interventions, and surgery. Rehabilitation for children with HCP takes many forms, commonly focusing on physical therapy and occupational therapy methods designed to increase range of motion, motor activation and strength, improve sensory perception, and improve performance of activities of daily living. Therapy commonly takes place in an outpatient clinical setting, and it is typical for therapists to provide a home exercise program in order to reduce the number of required clinical visits. Therapy focuses on the particular needs of individual patients, and may include strengthening exercise, balance exercise, electrical stimulation methods, passive motion of the joints, and the use of assistive devices. New therapeutic methods are in constant development, and determining effectiveness of rehabilitation programs for individual patients requires precise evaluation of UE behavior before, during, and after rehabilitation. Table 1.2

provides a survey of common techniques for UE rehabilitation in HCP and includes findings

regarding the efficacy of various methods.

Table 1.2. Survey of Common Rehabilitation Techniques in Hemiplegic Cerebral Palsy

Author(s)	Focus	Methods	Key Findings
Aisen et al. [34]	Rehabilitation methods – clinical review	Symptoms of focus include motor weakness and abnormal tone	Rehabilitative methods include strengthening, stretching, task-specific activities, functional neurostimulation, and orthotics
Deon & Gaebler-Spira [36]	Treatment of movement disorders in children with HCP	Symptoms of focus include hypertonia and decreased selective motor control	Passive stretching reduces excess tone & increases joint range of motion
DeLuca et al. [56]	Constraint-induced movement therapy (CIMT)	n=18 children with HCP, casting used to constrain unaffected limb	CIMT was effective in improving UE performance based on clinical evaluation metrics
Miller [58]	Clinical survey of rehabilitation techniques for children with CP	Strengthening exercises tailored to specific kinematic deficits	Shown to increase performance in children with CP, reduces musculoskeletal weakness
Miller [58]	Clinical survey of rehabilitation for children with CP	Intrathecal baclofen pumps; neuro-inhibitor	Shown to reduce spasticity and dystonia
Novak et al. [61]	Comprehensive review of interventions for children with CP	Assessed all interventions and categorized based on quality of evidence of clinical effectiveness; categories: highly effective and recommended, may be effective – measure results, or not effective – not recommended	Interventions found to be highly effective and recommended: - Anticonvulsants for seizures - Bimanual training - Botulinum toxin - Biphosphonates to suppress bone resorption - Constraint-induced movement therapy - Context-focused therapy - Diazepam to reduce spasticity - Fitness training - Goal-directed task-specific training activities - Home-based therapy - Occupational therapy

Surgical treatment of patients with UE dysfunction secondary to HCP is used to improve joint stabilization, restore range of motion, or balance overpowering torques across UE joints. Surgical procedures include joint fusion or reconstruction, muscle lengthening and tendon transfer [29]. The primary focus of surgical interventions is to reconfigure the musculoskeletal anatomy to allow more effective movement strategies. Like rehabilitation programs, surgeries are individually tailored to the specific musculoskeletal deficits of specific patients, and require high-quality clinical data to determine candidacy and gauge response to surgical interventions. Table 1.3 provides a survey of common surgical techniques for treatment of the upper extremity in children with HCP.

Table 1.3. Survey of Common Surgical Techniques in Hemiplegic Cerebral Palsy

Author(s)	Focus	Methods	Key Findings
Davids et al. [57]	Surgical management of thumb deformities in HCP	n=33, various surgical approaches depending on patient specifics: including muscle release, arthrodesis, muscle and tendon rerouting and tensioning	SHUEE showed significant improvements in static and dynamic thumb alignment after surgery; surgical techniques can improve hand performance in children with HCP
Smitherman et al. [9]	Functional outcomes of UE surgery in HCP	n=139 procedures, non-operative control group; procedures include tendon transfer, arthrodesis, capsuloidesis, web release, rerouting, and muscle lengthening surgeries	SHUEE showed significant improvement post-surgery, insignificant change in control group, and was used as surgical planning tool; surgeries improved hand and wrist functionality in children with HCP
Koman et al. [29]	UE surgeries – clinical review	UE surgeries focus on shoulder (stabilization & internal/external rotation), elbow (stabilization & extension), forearm (supination), wrist (stabilization & extension), thumb (stabilization, extension, & adduction), and fingers (flexion & swan-neck deformities)	Typical procedures include joint fusion, joint reconstruction, tendon/muscle lengthening, transfer, or release, depending on specific motion deficits

Author(s)	Focus	Methods	Key Findings
Miller [58]	Clinical review of UE surgical techniques for children with HCP	Shoulder Techniques	For severe adduction contracture, adductor lengthening surgery; for severe humeral internal/external rotation, humeral de-rotation osteotomy surgery
Miller [58]	Clinical review of UE surgical techniques for children with HCP	Elbow Techniques	For elbow flexion contracture, biceps tendon lengthening surgery
Miller [58]	Clinical review of UE surgical techniques for children with HCP	Forearm Techniques	For severe pronator contracture, pronator release or transfer surgery
Miller [58]	Clinical review of UE surgical techniques for children with HCP	Wrist Techniques	For wrist flexion contracture, flexor carpi ulnaris transfer or lengthening surgery
Miller [58]	Clinical review of UE surgical techniques for children with HCP	Hand Techniques	For thumb adduction contractures, thumb adductor lengthening or web-space lengthening or Z-plasty surgeries; for thumb abduction, palmaris longus or brachioradialis transfer surgeries

Objective assessment of upper extremity motion is an important factor in determining candidacy for surgery in HCP patients. The complex movements of the upper extremity require evaluation to occur in a standardized system [3], which may include clinical evaluations or motion analysis.

C. THERAPEUTIC MANAGEMENT INTO ADULTHOOD

It is important to consider individuals with HCP who have transitioned to adulthood and face the challenges of longer-term care, maintenance of mobility and the ability to perform ADL [50]. As therapies advance and research expands scientific understanding of HCP and rehabilitative processes, children with HCP are increasingly active in the community, have greater access to employment, and are participating more in recreational activities, which further enlarges the need to consider adult populations in rehabilitative efforts. Of particular concern for the aging population of individuals with HCP are diminished resources for support from insurance and healthcare providers and the need for a longer-term care perspective. Also important to recognize are the prohibitive costs associated with long-term therapy and rehabilitative care [51] for the uninsured or underinsured. The Kinect-based system developed here seeks to resolve these discrepancies by providing advanced rehabilitative and evaluative technologies at very low cost, with the ability for the system to be used at home.

III. UPPER EXTREMITY BIOMECHANICS AND REHABILITATION

This section provides a comprehensive background of the anatomy and physiology of the upper extremity and an in-depth analysis of neurorehabilitation, including motor re-learning and neural plasticity, and justification for quality rehabilitation and performance monitoring, including considerations of ADL that are important to individuals with HCP and physiological changes resulting from HCP and the rehabilitation process. A relatively broad array of information must first be considered in order to adequately present a case for the advancement of evaluation of UE dysfunction in individuals with HCP and neurorehabilitation knowledge as it relates to affected arm and hand functionality. The anatomical and physiological function of upper extremity movement and coordination and the basic understanding of neural rehabilitation provide a basis from which current clinical and research practices may be evaluated and new directions proposed.

A. UPPER EXTREMITY ANATOMY AND PHYSIOLOGY

The anatomy of the upper extremity requires complex coordination of the nervous, muscular, and skeletal systems, which together allow the arm and hand to serve its many functions, ranging from gross movements to fine manipulation of objects. Any investigation of restoration of UE function in children with HCP must begin with a review of the underlying anatomical and physiologic design of the human arm and hand, thus providing a basis from which both the extent of dysfunction before rehabilitative or surgical intervention and the extent of recovery after such intervention can be quantified. An additional concern is the longer-term physiological changes in bone, muscle, and neural tissue associated with atypical neuromusculoskeletal activity common in individuals with HCP. The intent of this section is to present the concepts necessary to understand UE function in terms of musculoskeletal structure, sensorimotor control, physiological change, and the interrelationship of the skeletal, muscular, and nervous systems.

The skeletal structure of the arm and hand has two primary functions: to allow mobility to the skeletal structure through joint articulation, and to tolerate the forces imposed by activity. The hand and wrist are composed of the carpals (lunate, pisiform, triquetrum, hamate, scaphoid, capitate, trapezium, and trapezoid), the metacarpals (first, second, third, fourth, and fifth), and the phalanges (proximal, middle, and distal--total 14), shown in Figure 1.1, all of which connect to the forearm (radius and ulna) through the wrist joint, which connects the radius, scaphoid, and lunate.
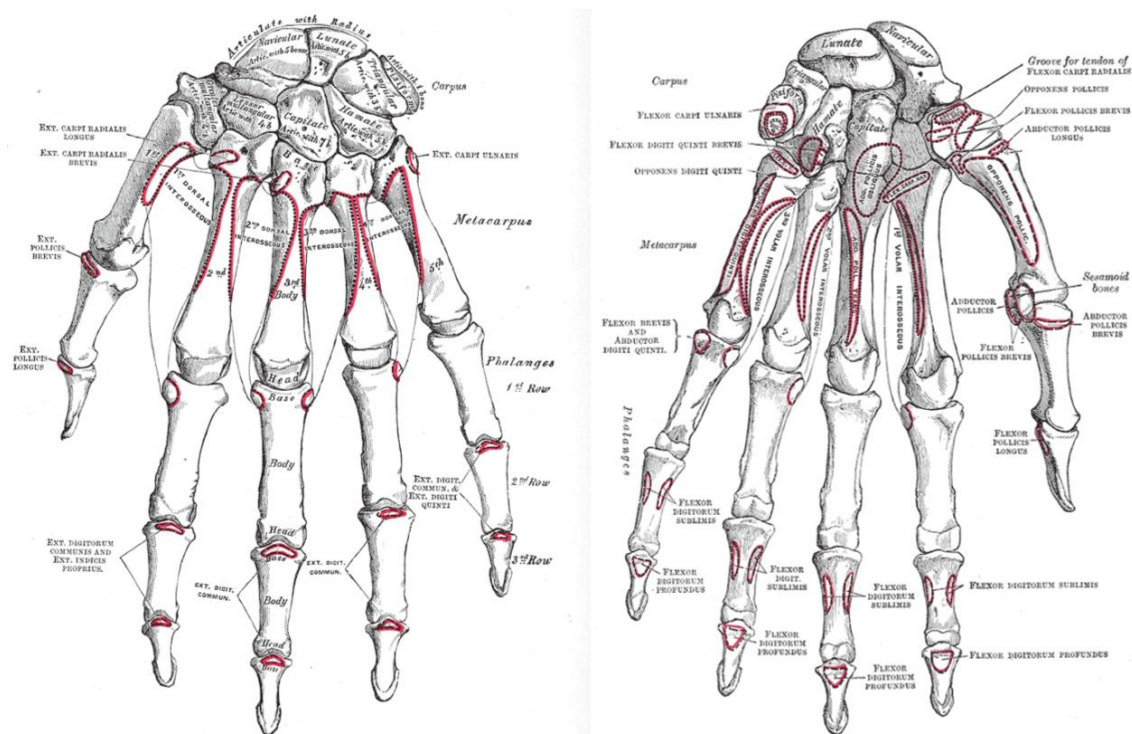
Figure 1.1. Bones of the Wrist and Hand, Dorsal (left) and Volar (right). [46]

The skeletal structure allows certain degrees of freedom in the wrist and hand. The wrist is capable of motion in the sagittal plane (flexion and extension) and coronal plane (radial deviation and ulnar deviation). The second through fifth digits are capable of flexion/extension at the individual joints and abduction/adduction at the metacarpal-phalangeal joint. The thumb is capable of flexion/extension, abduction/adduction, and opposition/reposition. The articulations of the hand and wrist are complex, and from a clinical evaluation perspective this complexity makes tracking fine anatomical motions difficult, especially considering the wide anthropomorphic variations in subjects.

The arm (humerus) is connected to the forearm through the elbow joint and to the trunk through the shoulder joint. Arm anatomy is demonstrated in Figure 1.2. Ligaments stabilize the joints and provide limits to the range of motion possible at each joint, demonstrated for the hand and wrist in Figures 1.3 and 1.4, respectively.
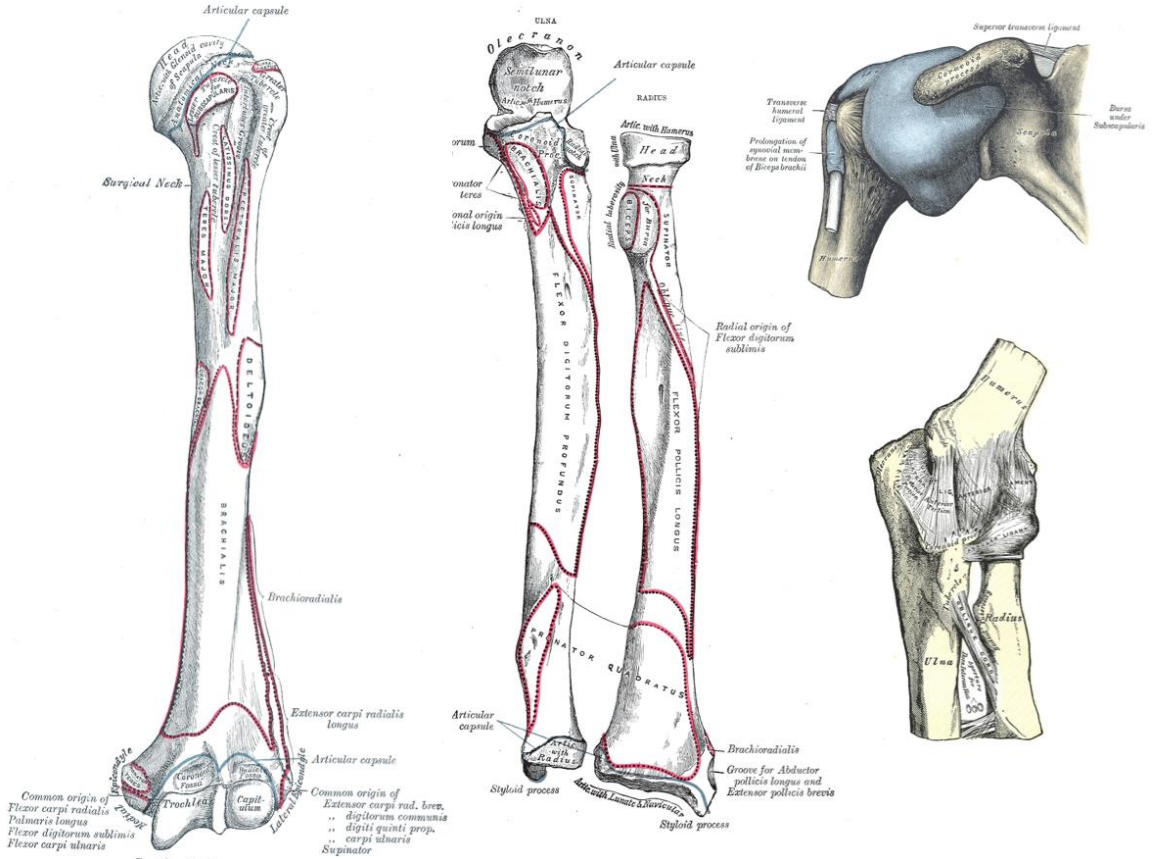
Figure 1.2. Skeletal Anatomy and Articulations of the Arm: Humerus (left), Radius & Ulna (center), Shoulder Joint (top right), and Elbow Joint (bottom right) [46]
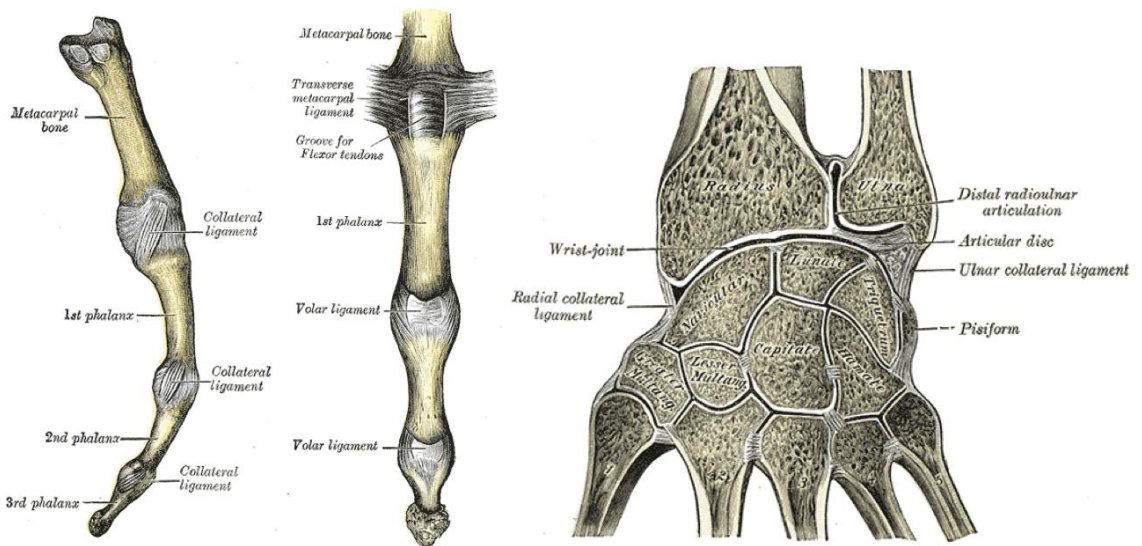
Figure 1.3. Ligaments of the Digits (left) and Carpal Bones (right). [46]

The shoulder joint is capable of motion in the transverse plane (internal and external rotation), the sagittal plane (flexion and extension), and the coronal plane (abduction and adduction). The elbow is capable of motion only in the sagittal plane (flexion and extension), and the forearm allows motion in the transverse plane (pronation and supination). The skeletal structure of the hand and wrist provides the strength, stability, and range of motion necessary for ADL.
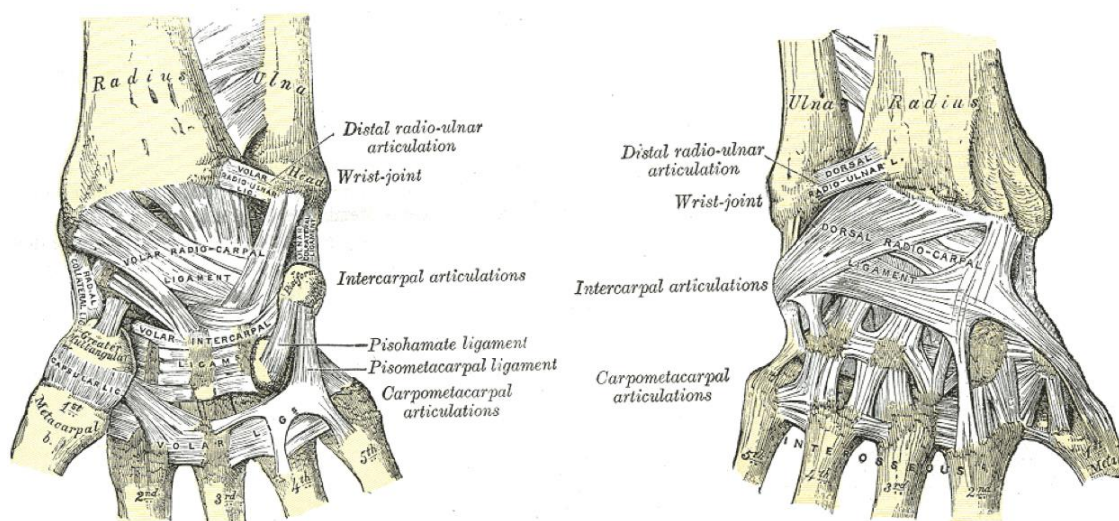
Figure 1.4. Ligaments of the Wrist, Anterior View (left) and Posterior View (right). [46]

The size and mass of bone tissue depends on the process of bone remodeling, which includes bone resorption, the breaking down of bone by osteoclasts, and bone osteogenesis, the rebuilding of bone by osteoblasts. Bone growth during youth is a direct result of greater bone osteogenesis and less resorption. The opposite is true as we age, with resorption exceeding osteogenesis, resulting in decreased bone mass, a condition referred to as osteoporosis. The rate of bone remodeling is directly related to the frequency and intensity of usage the bone experiences, physiologically recognized as mechanical strain. Unbalanced joint torques in individuals with HCP can result in bone torsional deformities and joint instability. Such skeletal abnormalities typically require surgical osteotomies or joint fusions to correct. Longer term UE

non-use and muscle imbalance can result in decreased bone mineral density beyond what occurs in the typical aging population. Thus, the remodeling rate is altered in individuals with HCP, when movement and resultant strain placed on bone is severely decreased, resulting in bone resorption and increased fracture potential adding to the already significant changes in functionality.

The muscular structure of the arm, forearm, wrist, and hand serves to actuate motion and provide stabilization of the skeletal structure. Muscular anatomy is demonstrated for the hand in Figure 1.5 and for the forearm in Figure 1.6. Muscles responsible for wrist and hand motion generally originate in the humerus, radius, or ulna, and the functions of these muscles actuate a skeletal degree of freedom of the wrist and hand, with some muscles performing multiple functions.
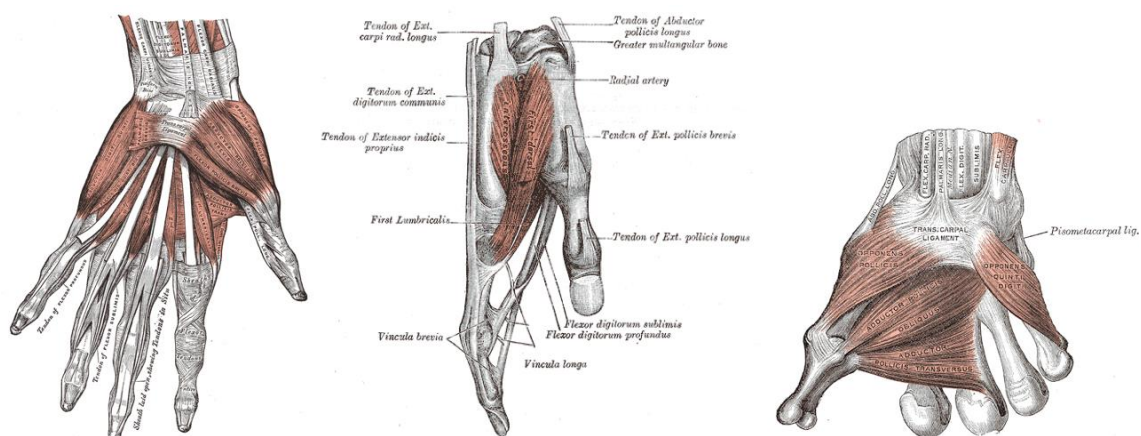
Figure 1.5. Muscles of the Hand. [46]

Muscles generally attach to the skeletal system through tendons. The muscular system adds elasticity to the rigid nature of the skeletal system and allows muscles to provide functional movement and a degree of motion damping. Muscles interface with the central nervous system at the neuromuscular junction, which provides the electrical impulses—action potentials—to effect contraction of the muscle.
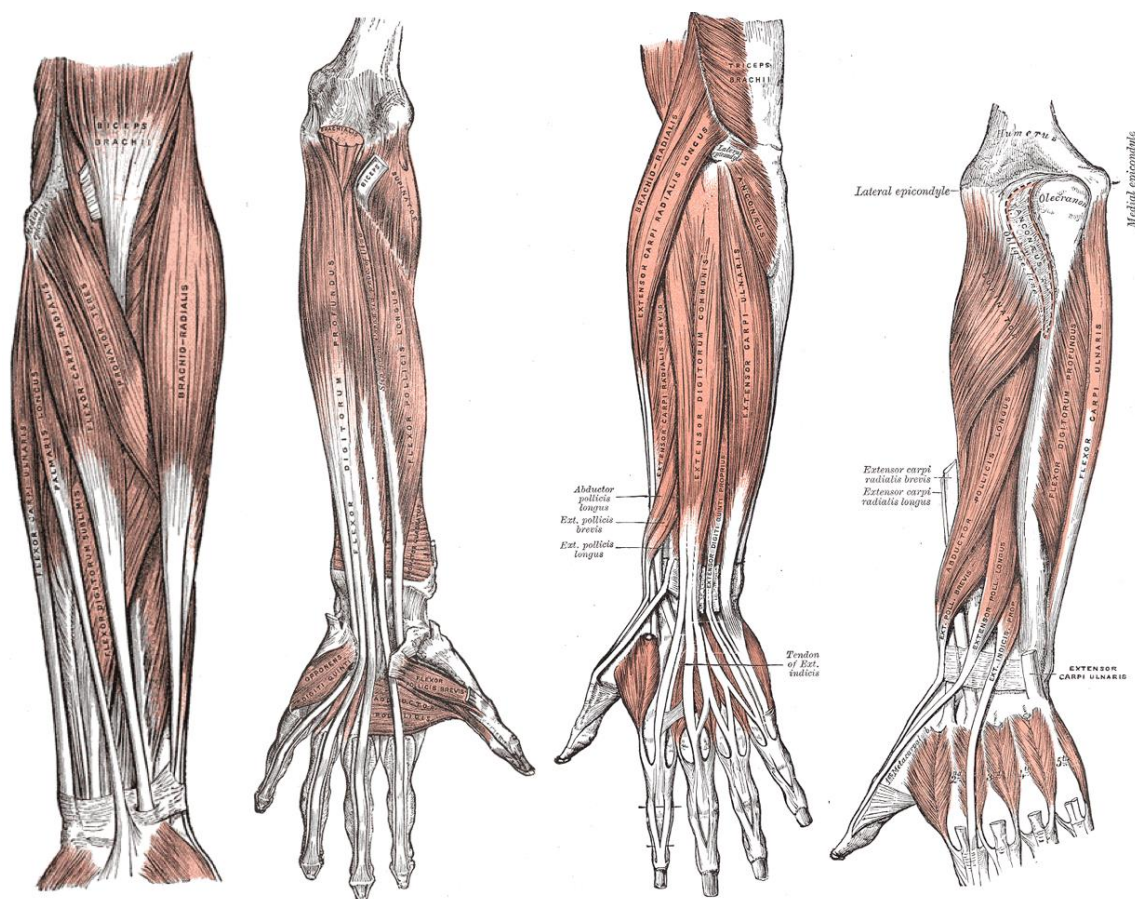
Figure 1.6. Muscles of the Forearm. [46]

Like bone, muscle also undergoes physiological change as a result of usage through the processes of atrophy (loss in muscle mass) and hypertrophy (gain in muscle mass). In general, increased stimulation of the muscle tissue results in hypertrophy, and decreased stimulation results in atrophy. Reduced muscle activity due to age, disability, or medical conditions such as HCP are characterized by reduced movement, whether through physical condition or reduced neural action potentials, and this reduced muscle usage makes muscular atrophy an important concern, especially if the condition persists for an extended period of time, as cerebral palsy typically does. In addition, atypical increased stimulation can result in hypertonicity which may be further characterized as spasticity, dystonia, or rigidity [59].

Motor function and sensory perception in the hand and wrist are achieved through the somatic nervous system, which consists of somatic sensory neurons and voluntary motor neurons.
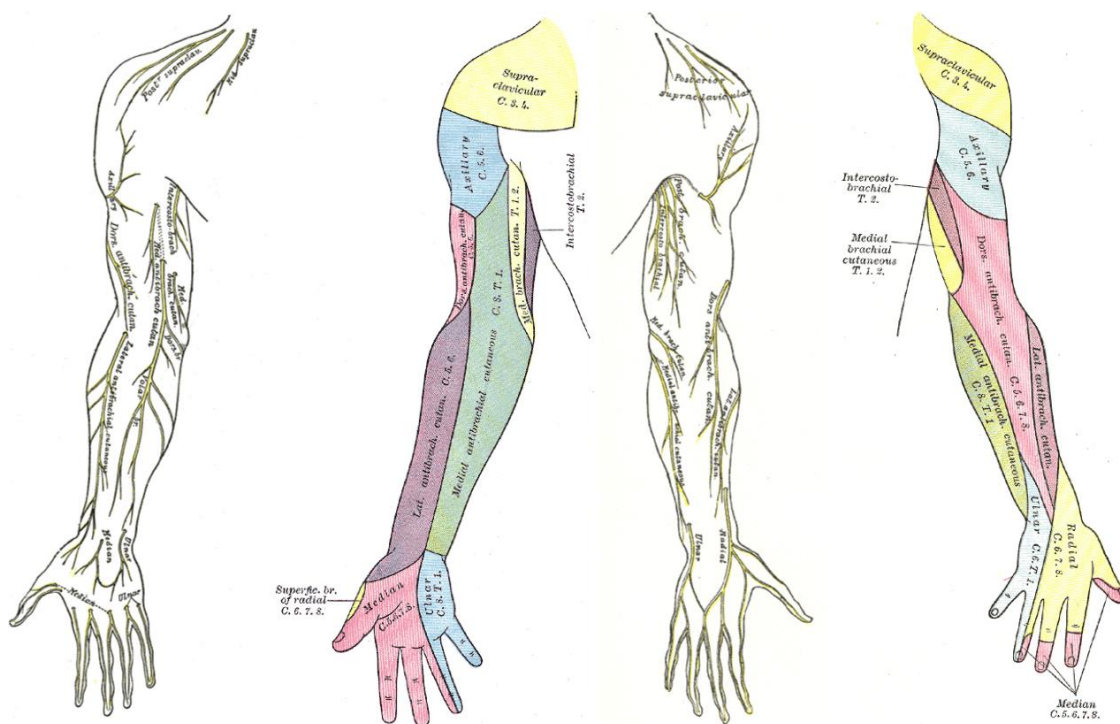
Figure 1.7. Innervation of the Arm and Hand, Anterior (left) and Posterior (right). [46]

The sensory and motor innervation of the hand, wrist, and forearm, illustrated in Figures 1.7 and 1.8, consists of the median, ulnar, and radial nerves, which branch to innervate individual muscles and sensory receptors. Sensory receptors important to hand and wrist function include exteroceptors, which are located cutaneously and provide pressure, pain, temperature, and vibration sensation, and proprioceptors, which are located in muscles, joints, and tendons to provide length and tension sensation. Both sensory types are vital for complete interaction with the environment and appropriate force modulation. Hoon et al studied sensory deficits in children with CP, and found that both sensory and motor functions are affected [60]. Imaging metrics used in the research were greatly associated with clinical measures of sensory function, and degree of sensory pathology using diffusion tensor imaging had strong correlation with measures of

functional severity. The sensory impairments resulting from HCP further exacerbate the ability of affected individuals to obtain complete interaction with their environment beyond reduced motor control.
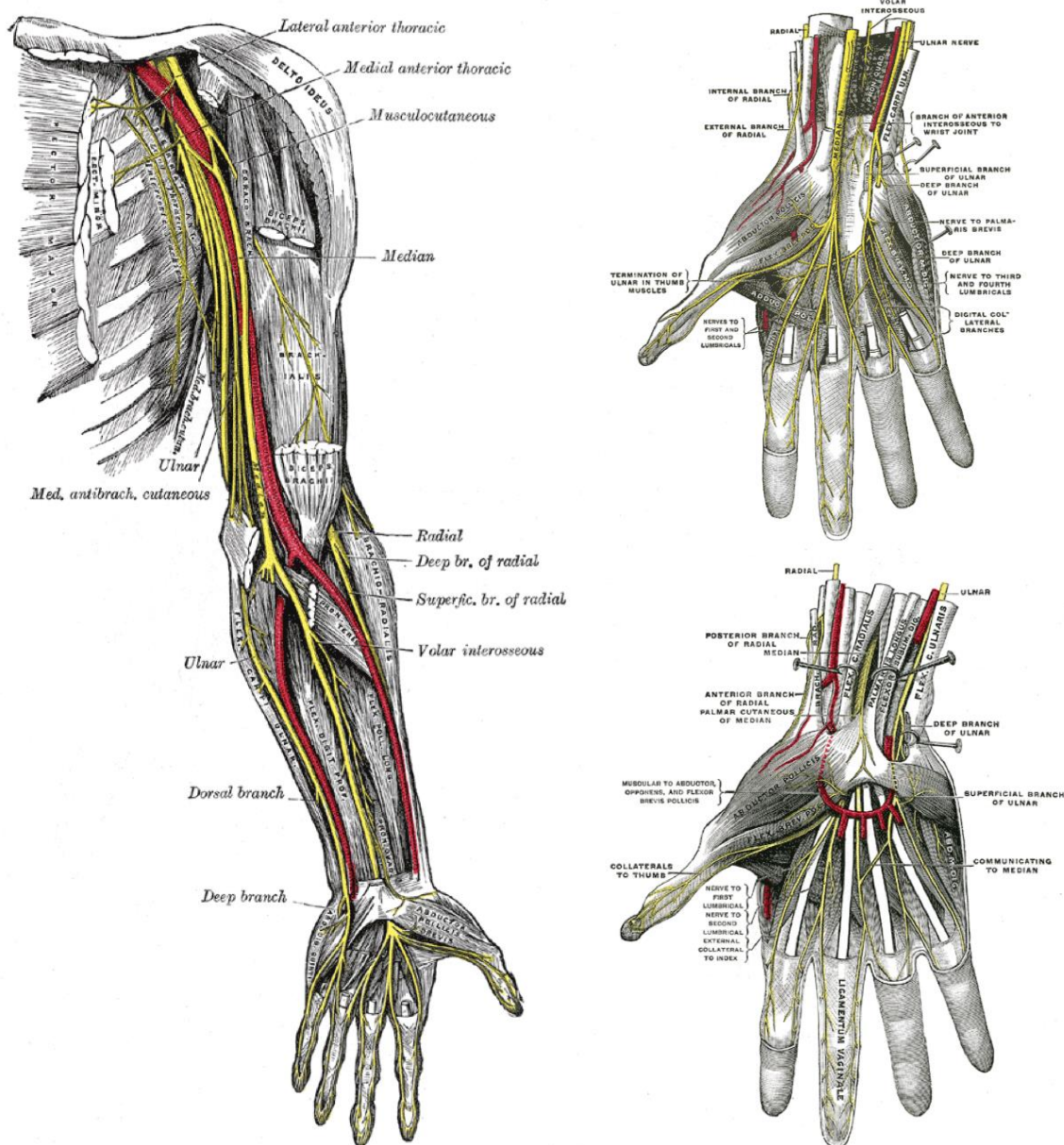
Figure 1.8. Nerves of the Arm and Hand [46]

The central nervous system includes the brain and spinal cord and facilitates the ascending sensory pathways and descending motor pathways. Examples of two predominant

sensory (dorsal column-medial lemniscus) and motor (corticospinal) tracts responsible for integrating ascending/descending information are shown in Figure 1.9. The cerebrum contains somatosensory and motor cortices, where motor impulses are sent and sensory impulses received, as well as areas of integration where these signals are processed and disambiguated. Sensory and motor neurons then travel through the spinal cord where they are distributed to a specific region of the body. For the hand and wrist, this path exits through the fifth through eighth cervical and first thoracic nerve roots and through the brachial plexus, where the median, radial, and ulnar nerves originate.
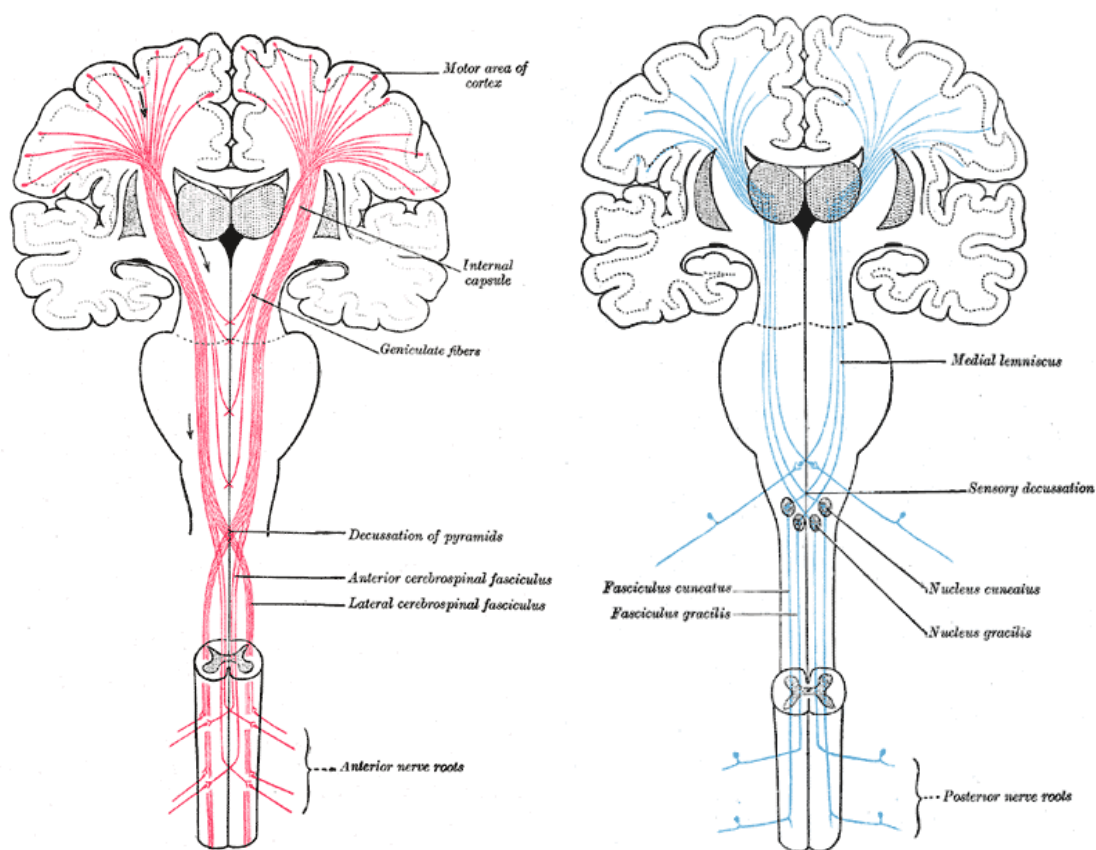
Figure 1.9. Corticospinal (Motor) Tract (left) and Dorsal Column-Medial Lemniscus (Sensory) Tract (right). [46]

Similar to skeletal and muscular tissue, the nervous system changes over time, a change known as neural plasticity. The underlying processes are not as well-documented as bone

remodeling and muscular atrophy and hypertrophy. Nerve regeneration (the ability to grow

additional neurons or repair damaged ones) is considered to be limited but plasticity (functional

change in nerve behavior as a result of other changes) is possible. These mechanisms will be

covered in greater depth later in this chapter.

Three interdependent systems act to allow functionality of the hand and wrist in human

motion: the skeletal system, which allows mobility through articulation and tolerates applied

loads, the muscular system, which actuates motion and provides stability to musculoskeletal

structure, and the somatic nervous system, which provides motor control of the muscles and

sensory information through cutaneous sensation and proprioception.
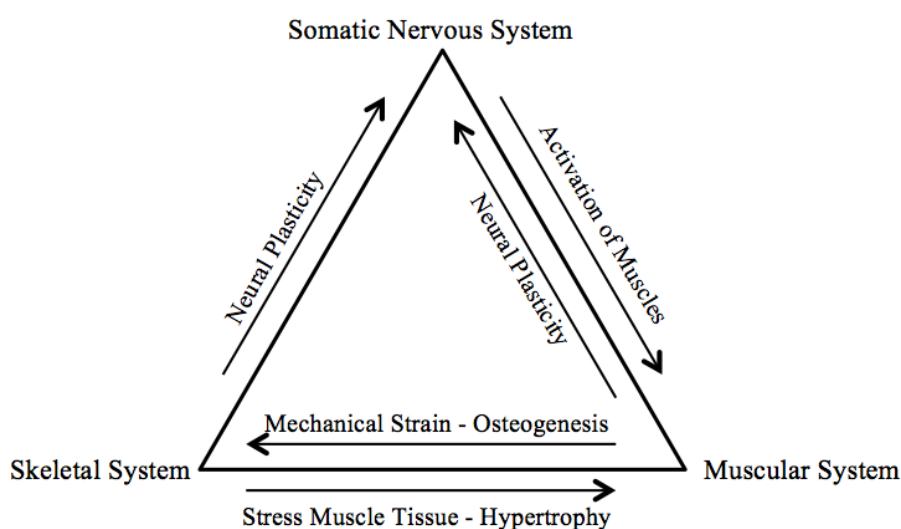
Figure 1.10. Interaction of Nervous, Muscular, and Skeletal Systems in Rehabilitation

The activity of the neuromusculoskeletal system is triangular in nature, as depicted in

Figure 1.10, and a disruption in any of the three systems inherently affects the others. For

instance, a disease of the muscle such as muscular dystrophy will result in decreased mechanical

strain on the bone, causing bone resorption and decreased neural activation, resulting in neural

plasticity. Further, a disease of the bone, such as osteogenesis imperfecta, may increase risk of

fractures, which in turn reduce or eliminate usage of muscles during recovery, causing atrophy

and neural plasticity. Diseases of the nervous system, such as HCP, may reduce or eliminate action potentials to muscles, causing muscular atrophy, and, due to decreased mechanical strain on the skeletal system, bone resorption.

The hand and wrist also are greatly affected by disruptions in neuromusculoskeletal function resulting in changes to fine motor control and grip and pinch strengths. Reduced coordination in neuromuscular activity results in imbalanced torques across joints, which causes decreased joint stability and poor movement quality. Combined, these effects result in joint weakness, contracture, or development of compensatory strategies to accomplish functional tasks, with long-term results including joint instability and fixed deformities, all of which cause significant changes in individual abilities in ADL performance.

B. UPPER EXTREMITY NEUROREHABILITATION

Neurorehabilitation refers to the restoration of neural capability in subjects that have sustained a decrease or elimination of neural function, and includes research into the mechanisms of neurocognitive rehabilitation, the restoration of neural tissue function, and neural plasticity, the change in function of neural tissue in adaptation. A study of the mechanisms of neurorehabilitation provides an additional basis for the understanding of improvements in upper extremity functionality in subjects with HCP and, combined with neuromusculoskeletal anatomy and physiology and an understanding of the mechanisms of neural control, completes the background information required to understand hemiplegia and the underlying physiologic mechanisms of rehabilitation of the upper extremity.

Neurocognitive rehabilitation and motor relearning refer to the processes by which the nervous system restores function to neural tissue damaged or temporarily inactivated by a disorder or functional interruption of activity. The recovery of neural function in this manner involves neurons regaining similar function to normal or pre-injury conditions, and as a result the body can move and sense using the same neural pathways present prior to neural injury.

Neural plasticity refers to the adaptation of nervous tissue in response to neural damage, injury, or changes in usage. Neural plasticity is thought to be a compensatory mechanism where neuronal activity of a damaged area of the brain is transferred to nearby areas that are unaffected or less affected. Transferring neuronal activity to less or unaffected areas of the brain results in continued transmission of the sensory and motor signals necessary for movement. Plasticity occurs both in the short term, where the sensory and motor signals of the damaged region are rerouted to nearby areas after stroke, for instance, and the long term, where these new signal pathways undergo further plasticity in response to rehabilitation and increased use [42]. Neural plasticity is not limited to rehabilitation after injury, but is inherently involved in learning processes, and the brain experiences physiologic change similar to muscular atrophy/hypertrophy and bone remodeling in response to usage amount, usage intensity, repetition, age, and other considerations [43].

Scientific understanding of the human nervous system is incomplete and constantly evolving, as is the understanding of cerebral palsy and the underlying processes that allow neural rehabilitation in response to treatment. After neural tissue has been damaged, the processes of rehabilitation begin, taking the form of neural recovery and neural compensation. In combination, these two mechanisms allow affected individuals to possess some degree of sensorimotor recovery, a recovery heavily influenced by the intensity and protocol of rehabilitative intervention. The investigation of rehabilitation intervention effectiveness, through the plethora of measurement methodologies available, provides additional insight into neural behavior, and seeks an optimized treatment strategy.

C. IMPORTANCE OF UPPER EXTREMITY FUNCTION

The hand and wrist are complex biomechanical systems vital to independent performance of ADL. As seen in previous sections, the severity and location of the neural damage associated with HCP dictate the perceptible effects on functional use of the UE during ADL. One ADL

significant to overall patient satisfaction is mobility, whether through ambulation, use of an assistive device, use of a wheelchair, or the ability to transition among positions. Even when independent ambulation is achieved, the UE is required during higher level gross motor functional skills such as grasping a handrail when negotiating stairs or using playground equipment. Assistive devices, such as walkers or crutches, support ambulation, but many of these devices require a firm grip and stability in the wrist joint. Manual wheelchairs require high-level hand and wrist function to operate the propulsion wheels and facilitate turning. Electrically powered wheelchairs eliminate the necessity for strong hand and wrist motions, but still require the hand and wrist to provide fine motor control for joystick operation and interaction with environmental obstacles (door handles, elevator buttons, light switches, and many others).

Patient transfers (to and from wheelchair, bed, toilet, or other seating) are an additional aspect of mobility that must be considered. While these tasks are not likely to require significant fine motor control or dexterity, grip strength is very important for the patient to remain stable throughout the transfer. Thus, hand grip strength and wrist flexion/extension and pronation/supination stability are key to successful grasping of assistive bars or railings (on wheelchairs, bed rails, or bathroom wall-mounted support bars), and maintenance of stability during the transfer. Generally one hand and wrist are affected in individuals with HCP, but the uninhibited use of two hands will make self-transfer a significantly less difficult and dangerous process.

Self-care tasks are very important to the overall physical and psychological health of the patient and include such activities as bathing, grooming, dressing, toileting, cooking, cleaning, eating, and managing medications. While many of these activities are certainly possible to perform one-handed, most will be easier and safer if performed bi-manually. During dressing, for instance, donning and doffing clothing one-handed would be significantly more difficult than two-handed, especially considering closure devices such as buttons and zippers. Physical and occupational therapists in rehabilitation settings often focus on improving performance of these

self-care activities of daily living, since independence is so important to physical and

psychological health.

Technological devices with QWERTY-style keyboards, as well as mobile phones and

devices, are highly dependent on operation with both hands, and require significant dexterity to

operate with even moderate speed. Computer mice and track pads also require fine motor skills

for aiming and clicking. In current society, the vast majority of people use technological devices

with a keyboard input on a daily basis and, as the population ages, eventually nearly all adults

with HCP will need to use keyboard-input devices frequently as well. Considering that most

keyboards are designed specifically to be used with both hands, compensatory strategies or

assistive technology will need to be considered for individuals with HCP. Rehabilitation methods

focused on the hand and wrist can provide functional improvement that may increase

technological device operation capability and speed, whether or not these improvements

eventually result in normal levels of hand and wrist functionality. In addition, specialized

computer keyboards designed for one-handed use exist, but they incur an additional expense and

learning curve for fast operation.

Limited functional independence can have significant effects on overall quality of life for

individuals with HCP. As previously mentioned, tasks related to ADL may be very difficult or

even impossible, thus limiting participation in hobbies, social activities, and social interactions

[44]. Reduced or absent hand and wrist function in individuals with hemiplegia has devastating

effects on leisure activities that require bilateral use of the hands. Thus, from a psychosocial

perspective, chronic movement disorders affecting the UE can be associated with significant

social isolation and remove enjoyment from the lives of those affected.

HCP causes a distinct reduction in capability of the nervous system, which in turn affects,

over time, the muscular and skeletal systems because of the interdependence of the three systems.

In children with HCP, atypical neuromuscular activity includes both increased neural activation,

causing hypertonicity, and reduced neural activation, causing limitations in selective motor

control and musculoskeletal weakness. Combined, these effects result in inefficient movement patterns, decreased functional independence, and development of compensatory strategies which ultimately lead to non-use, contracture, and deformity. Thorough and early rehabilitation focuses on minimizing these important physiologic effects.

Previously, it has been shown that hemiplegia and sensory loss cause a decrease in motor activation and sensory feedback, including proprioception, and related effects such as muscular atrophy. Sensorimotor control is quite complex in the hand and wrist, due to the complicated framework and the need for extremely fine movements when interacting with the environment. HCP not only impacts the overall strength and sensitivity of hand and wrist movements, but can reduce or eliminate capabilities to perform some of the finer movements necessary for full use of the hand and wrist in environmental interaction.

One of the most significant difficulties in sensorimotor-impaired individuals is a lack of force control, a reduction in muscular control of forces applied to objects accurately, steadily, and matched to the specifics of the activity (in gripping fragile objects, for instance) [47]. This significantly impacts capability of affected individuals to perform activities of daily living that involve manipulation of small or fragile objects, such as utensils for eating, writing instruments, or personal hygiene implements. Hand shaping during reaching and grasping, and conformation to objects held in the hand, also referred to as palmar arch modulation, have been shown to be significantly decreased in hemiplegic patients [48]. Deficits in hand shaping capability affect those activities of daily living that require grasping of irregularly shaped objects, such as beverage containers, the handles of walkers, canes, and wheelchairs, and medication bottles. Hemiplegia also has the potential to reduce smoothness in hand movements, causing abrupt movements while tracking along a desired path, reducing the speed and effectiveness of hand and wrist movement [49]. Jerkiness in movement would make certain activities, such as picking up and drinking from a glass, more difficult.

The implications of reduced hand and wrist sensorimotor control in patients with HCP are significant, and include a reduction in environmental activities of daily living (mobility and self-care), technological and communication activities, participation in social activities and hobbies, and significant physiological changes (muscle atrophy, bone osteoporosis, reduction in fine motor control). Clinical rehabilitation demonstrates both qualitative (improvements in ability to perform activities of daily living) and quantitative (improvements in results of kinematic analysis) changes in sensorimotor function of the hand and wrist, which benefits the independence and quality of life experienced by individuals with HCP.

The goal of returning functional ability is facilitated through neurorehabilitation of the hand and wrist, an area of research with multiple approaches and no complete solutions or optimized treatment strategies. Novel rehabilitation strategies have the potential to increase the completeness of recovery as well as decrease the time and effort required to achieve it.

IV. UPPER EXTREMITY EVALUATION

Accurate and reliable evaluation of functional performance is an important factor in initial and ongoing care of children with HCP. In terms of the UE, previous sections have described in detail the anatomy and physiologic changes resulting from disease or rehabilitation. Clinical tools may be used to determine the extent of these changes in individual patients. Here, the most common evaluation tools in clinical use are reviewed. These tools allow clinicians to determine functional deficits, design a rehabilitation program or surgical approach tailored to specific patients, and objectively evaluate the effectiveness of ongoing interventions. Evaluation methods typically include clinical task-based evaluations and kinematic motion analysis technologies, each of which has multiple benefits and limitations in clinical applicability.

A. CLINICAL EVALUATIONS

Clinical evaluations of UE function in children with HCP are used to determine the quality and quantity of motion in the affected upper extremity and to measure the effectiveness of

rehabilitative or surgical intervention. UE motion is complex, and evaluation with accuracy and consistency requires recognition of complex movement patterns during functional tasks [9]. A wide array of clinical tools are currently used to assess movement strategies employed during the completion of functional tasks [10]. It has been suggested that both the upper arm and forearm should be evaluated alongside the hand and wrist in individuals with HCP to ensure a complete description of UE capability [13], thus ensuring that both broad and fine motor activities are represented.

Clinical examination tools used for individuals with HCP include measures of function and measures of impairments such as muscle strength and tone, passive and active joint range of motion, and bony deformities [33]. Klingels et al. have described necessary clinical evaluations of UE performance in patients with HCP as being both capacity-based, referring to the ability of the patient to execute tasks in a standardized environment, and performance-based, the real-world spontaneous use of the affected extremity during non-standardized everyday activities [12]. This is an important distinction to recognize in the rehabilitative process, where continued use of the affected limb without being prompted to do so may improve ADL capability in patients with HCP. The Shriners Hospitals for Children Upper Extremity Evaluation (SHUEE), for example, was designed to indicate both whether and how a subject can complete functional tasks in scenarios that are standardized and controlled but still attempt to represent realistic ADL, thus operating as both a measure of technical metrics and functional task performance [2]. However, this tool is used in a standardized clinical environment rather than measuring performance in a real-world setting.

Clinical evaluations of UE function performed by therapists typically include activities designed to obtain information that is clinically relevant to patient condition, in a time- and cost-effective manner [10,11]. Evaluations normally result in a numerical score of overall task completion and an examination of UE impairments to provide clinicians with information to improve clinical care and provide family and caregivers with semi-quantitative status updates

[11]. Scores are generally determined either during testing or via video recorded performance by therapists trained to analyze subtleties in activity movements [10]. These clinical evaluations have the significant limitation of being based on performance ranking scales rather than quantitative kinematics [31]. This introduces subjectivity into results based on observation by therapists [24,28,40] and reduces sensitivity of analysis [40] because movement quality is categorized using ordinal scales rather than continuous performance variables. Table 1.4 provides a survey of common UE evaluations designed for children with HCP.

Table 1.4. Survey of Clinical Evaluation Protocols for Hemiplegic Cerebral Palsy

Author(s)	Name	Method	Key Findings
Davids et al. [2]	Shriners Hospitals for Children Upper Extremity Evaluation (SHUEE)	Video-recorded evaluation, 16 activities of daily living focus in categories of grasp/release, spontaneous functional analysis, and dynamic positional analysis; scored from video later; uses ordinal scoring scales, ages 3-18	Validated method; easy to use in clinical environment; lack of sensitivity to detect change following intervention; potential for subjectivity in scoring
Vandervelde et al. [55]	ABILHAND-Kids	Questionnaire containing list of 21 ADL-based activities, patients select typical difficulty based on 3-level scale, designed for ages 6-15	Method is validated and demonstrates good detection precision
Klingels et al. [54]	Melbourne Assessment of Unilateral Upper Limb Function (MUUL)	16 ADL-based tasks tested in task categories reach, grasp, release, and manipulate, score is summed, ages 5-15	Interrater and intrarater reliable for evaluation of UE function in children with HCP
Klingels et al. [54]	Quality of Upper Extremity Skills Test (QUEST)	Criterion-referenced measurement tool, 34 movements tested in categories of dissociated movements, grasp, weight bearing, and protective extension, scores summed, ages 18mo-8yr	Interrater and intrarater reliable for evaluation of UE function in children with HCP

Author(s)	Name	Method	Key Findings
Wagner & Davids [10]	Assisting Hand Assessment (AHA)	Measures bilateral hand use, standardized test kit with toys, 22 areas of focus, video recorded and scored after, age 18mo-12yr	Validated and reliable test
Wagner & Davids [10]	Box and Blocks Test	Measures unilateral dexterity, blocks moved from one side of box to another, score is number of blocks moved in one minute, age 6 or older	Validated and reliable test
Wagner & Davids [10]	Canadian Occupational Performance Measure (COPM)	Interview during which patients discuss and rank top 5 problem areas prior to intervention, any age	Valid and reliable for a variety of conditions and ages – scores are compared to individual's past scores only
Wagner & Davids [10]	House Scale & Modified House Scale	Assessment of spontaneous usage (also a component of the SHUEE) on 9-point scale, designed for ages 2-20	Reliable

Overall, clinical evaluation protocols provide therapists with easy-to-use tools that can be used to quickly and inexpensively evaluate a patient's condition without resorting to more intensive methods. However, there is significant need for improvement of these evaluations to include more quantitative scoring systems and increased sensitivity to detect changes in functional performance resulting from intervention or disease progression.

B. KINEMATIC ANALYSIS

Three dimensional lab-based motion analysis allows quantitative reporting of multi-planar multi-joint kinematic limitations during UE functional task performance [22]. Analysis of upper extremity motion is complex due to multiple degrees of freedom and wide range of motion in the UE. The Vicon motion capture system is a standardized, validated system from which it is possible to evaluate other motion analysis platforms [5]. The Vicon system consists of multiple

cameras in a permanent laboratory setting that detect numerous passive markers placed on the subject. This system is extremely accurate and precise but has multiple limitations for repeated testing to monitor the status of children with HCP, including high cost, low portability, and necessity for markers attached to the patient's skin that may be uncomfortable or restrict UE movement [21].

Upper extremity motion characteristics in children with HCP can be determined through clinical motion analysis, but this is not as common as clinical UE therapist-led activity-based evaluations, due to technical limitations and a lack of defined, repeatable kinematic tasks with meaningful results [28]. It has been shown that quantitative motion analysis of the UE during functional task performance produces reliable and repeatable kinematic data, within and between sessions, as an outcome measure in patients with HCP [24,25] and can also differentiate between affected and unaffected arms in subjects with HCP or dominant and non-dominant arms in typically developing subjects [28]. In research studies, motion analysis can be used to quantify upper extremity performance before and after interventions to quantify improvements in patient response. Quantitative motion analysis is also useful when planning surgical interventions by pinpointing areas of interest and predicting response to certain surgeries. There is currently no validated clinical test to measure UE movement speed and dexterity in patients with HCP [2], but clinical motion analysis has the potential to quantify these important indicators. HCP is also characterized by different multi-joint coordination patterns during functional activities [20] and trunk motion as a compensatory mechanism when joint performance is reduced [21]. These changes may not be readily observed by clinical evaluations such as the SHUEE, which focuses on a single joint at a time, but are easily detectable by clinical UE motion analysis, which inherently includes all UE joints in typical models.

Difficulties in detecting and evaluating upper extremity kinematics include a larger variation in UE activity trajectory [15] due to a lack of easily described cyclic movements, in contrast to activities such as gait for the lower extremity which consists of fully defined patterns,

and anatomical redundancy and increased degrees of freedom in the upper extremity [24], thus allowing multiple feasible kinematic movement strategies for a given activity [22]. However, optimized kinematic strategies and observed movement trajectories are typically followed by populations of typically developing individuals [23]. Further, UE cyclic tasks tend to have large variation at beginning and end points due to lack of standardized cycle milestones, such as heel strike and toe off in gait [22,24,26]. In addition, marker-based systems may artificially limit UE motion due to marker interference with activity performance [20], and present issues relating to the small size and multiple degrees of freedom of segments [9], particularly in the hand, as well as relatively high velocity of movements [17] compared to the lower extremity. Markerless systems are also available, and remove marker-related limitations while providing accuracy comparable to marker systems for the shoulder and elbow, but slightly less accuracy in the wrist and hand [39] due to difficulties in tracking these small segments visually. Presentation of kinematics from UE activities is less intuitive than gait, due to lack of typical cyclic UE activities, and increased biomechanical complexity [15,40]. This causes difficulty in disseminating the results of kinematic analysis to surgeons, who typically require more detail on the specific musculoskeletal structures affecting movement. Interpretation of kinematic plots or statistics is less intuitive for UE motions [17] than for gait, for instance, but this has been alleviated with the development of International Society of Biomechanics (ISB) standards for UE kinematic reporting [18]. Calculation of population mean data in normal subjects for standardized tasks allows more robust analysis of affected subjects through standardized target metrics [16], thus providing therapists with benchmarks toward rehabilitation objectives. Table 1.5 provides a survey of research relating to the procedures of detecting upper extremity behavior through kinematic motion analysis.

Table 1.5. Kinematic Motion Analysis in Upper Extremity Detection

Author(s)	Focus	Methods	Key Findings
Klotz et al. [3]	UE motion capture during ADL performance	n=15 adults with CP and n=15 normal subjects, 10 ADLs performed, ROM of elbow, shoulder, and trunk measured	Adults with hemiplegic CP show reduced ROM at elbow, shoulder, and trunk compared to both normal subjects and unaffected limb; UE kinematic motion analysis is highly sensitive and can detect UE behavior during ADL performance
van Andel et al. [15]	3D kinematics of UE during ADL performance	n=10 normal subjects, 4 ADLs and 6 ROM tasks performed, joint angles measured for wrist, elbow, shoulder, and scapula using Optotrak active marker-based system	UE kinematic motion analysis methods are capable of measuring joint angles during typical ADL performance; there is a need for standardized reporting of UE results
Aizawa et al. [16]	3D kinematics of UE during ADL performance	n=20 normal subjects, 16 ADL tasks, joint ROM measured using FASTRAK electromagnetic system	UE kinematic analysis is sensitive to joint ROM and can be used as a basis for surgical and rehabilitation planning and outcome measurement
Rab et al. [17]	UE 3D kinematic analysis system development and evaluation	System developed to use surface markers and video-based detection	System validated; serves as precursor to more advanced current systems for UE kinematic analysis
Murgia et al. [19]	UE 3D kinematic analysis for movement and compensation strategies during ADL performance	n=6 normal subjects and n=5 subjects with distal radius fracture; thorax, shoulder, elbow, and wrist angles measured using Vicon system	Elbow and wrist ROM reduced with distal radius fracture; clinical motion analysis allows more effective surgical planning through quantitative data
Petuskey et al. [22]	UE 3D kinematic analysis for pediatric ADLs	n=51 typically developing children; 5 ADLs performed; UE kinematics measured with 8-camera system	Characterization of UE motion patterns for typical ADLs; demonstrates need for standardized protocol for UE kinematic processing

Author(s)	Focus	Methods	Key Findings
Mackey et al. [24]	Determining reliability of UE kinematics	n=10 children with HCP; hand to head and hand to mouth ADLs; measured with OrthoTrak 3D motion capture system	3D UE kinematic analysis is repeatable, and significantly accurate to be used for intervention planning and evaluation
Jaspers et al. [25]	Reliability of UE kinematics	n=12 children with HCP; 7 standardized tasks performed; measurements using Vicon system	High within and between session reliability shown; transverse plane showed more error than sagittal or coronal plane detection
Mackey et al. [28]	UE task performance deficits in HCP	n=10 children with HCP and n=10 normal subjects; hand to head, hand to mouth, and reach ADLs	System detected differences between affected and unaffected limbs and normal versus affected population; 3D kinematic analysis is more sensitive than clinical evaluations
Jaspers et al. [30]	UE movement characteristics in HCP	n=20 children with HCP and n=20 normal subjects; 8 ADL tasks; measurements using Vicon system	Children with HCP have longer movement durations, more trajectory variation, and lower velocity; 3D motion analysis can characterize details of motion trajectories
Jaspers et al. [40]	Quantitative UE measurements for HCP	Literature review; n=17 articles describing UE measurement techniques for HCP	Both active and passive marker-based optical tracking systems; systems are repeatable and highly sensitive to change

Overall, kinematic motion analysis provides accurate, precise, and quantitative data for clinicians, thus greatly increasing sensitivity to detect functional change, but typical lab-based systems are burdened by high cost, cumbersome marker systems, and complex operation requiring advanced training. There is significant need to provide quality kinematics in a system

that is simple to operate, while maintaining the clinical resolution needed to enhance decision-making capabilities of therapists and surgeons.

C. THE SHUEE

The Shriners Hospitals for Children Upper Extremity Evaluation (SHUEE) is a validated method of UE evaluation and was developed in 1996 to provide improved clinical information describing subject ability and performance of functional tasks based on ADL [2]. It evaluates spontaneous usage, alignment of UE segments, object grasp and release capability of the hand. The SHUEE is currently the only validated clinical test for individuals with HCP that includes detailed evaluation of thumb, finger, wrist, forearm, and elbow movement [12], and is designed to accommodate patients with HCP aged 3 to 18.

The SHUEE uses video-recorded standardized ADL, described in detail in the therapist manual [2], and performed by the subject using specific instructions from the therapist. The SHUEE takes approximately 15 minutes to complete. A therapist then evaluates a video recording of the session and scores a spontaneous functional analysis (SFA) for each task scored based on the Modified House Scale, dynamic positional analysis (DPA) based on position and range of motion of segments, and grasp and release analysis (GRA) based on object grasp and release capability at wrist flexion, extension, and neutral positions [2]. These values are recorded on standardized numerical SHUEE reporting forms.

SFA, DPA, and GRA are presented on scoring sheets as percentage scores to represent overall UE function. The SHUEE is able to detect functional outcomes of UE surgery [9], and has been applied to research studies, a survey of which is presented in Table 1.6 below. Davids et al., the developers of the SHUEE, admit that kinematic motion analysis during functional task performance would provide more accurate, reliable, and objective data than the qualitatively-based SHUEE. They also noted that the SHUEE may lack the sensitivity to detect changes in patient condition following therapeutic or surgical intervention [2]. However, limitations of

quantitative UE motion analysis using standard clinical motion capture systems discussed

previously limit the ready application of kinematic analysis to evaluations such as the SHUEE

without significant technological advancement.

Table 1.6. Key Research Involving the SHUEE

Author(s)	Focus	Methods	Key Findings
Smitherman et al. [9]	Functional outcomes of UE surgery in HCP	SHUEE performed pre/post-surgery, n=139 procedures, non-operative control group	SHUEE showed significant improvement post-surgery, insignificant change in control group; SHUEE can be used as a reliable clinical tool for surgical planning and evaluation
DeLuca et al. [56]	Outcomes of constraint-induced movement therapy in CP	SHUEE performed pre/post CIMT, n=18	In the SHUEE SFA, DPA, and GRA all showed significant improvement in scores consistent with other measures; SHUEE can be used to gauge effectiveness of rehabilitation therapies
Davids et al. [57]	Surgical management of thumb deformities in HCP	SHUEE performed pre/post-surgery, n=33	SHUEE showed significant improvements in static and dynamic thumb alignment after surgery; SHUEE can be used to gauge effectiveness of surgical interventions

In the current project, the SHUEE is used as both an exemplar evaluation to represent

typical functional tests for children with HCP for development of Kinect activities and as a key

component of inclusion criteria in normal population subject testing, where the SHUEE is applied

as a control test. Use of the SHUEE as a basis for developing activities for the Kinect-based

system in this project is ideal, due to the broad spectrum of upper extremity motions represented

and focus of the activities on typical activities of daily living. Quantitative enhancement of

SHUEE-derived activities allows confidence that the Kinect-based system is able to detect and

present clinically relevant metrics for upper extremity function.

V. MICROSOFT KINECT

The Microsoft Kinect was launched to the consumer market in late 2010 for video game control purposes, designed to allow interactive gaming using gesture-based control while tracking skeletal position, consistent with the trend in video games toward innovative game interaction beyond the traditional controller. Later, Microsoft realized the multitude of other commercial, gaming, and research applications for the Kinect hardware and released a Windows-based software development kit in 2011 [4]. The skeletal detection methods used in the Kinect hardware allow the system to be useful in a variety of roles, many of which have been explored through recent research and development with the Kinect.

A. HARDWARE
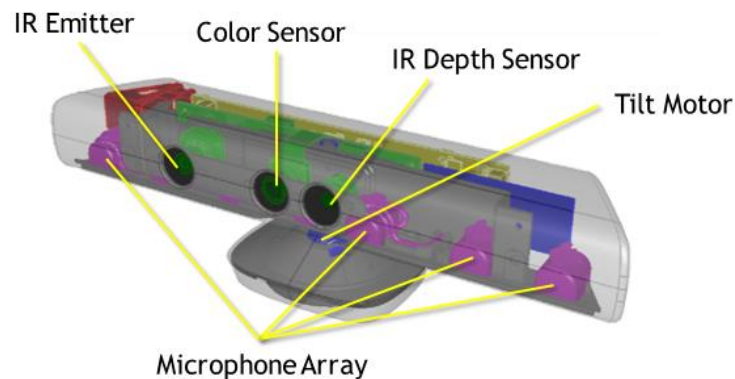
Figure 1.11. Hardware Components of the Microsoft Kinect Sensor. [4]

The hardware components contained in the Kinect sensor are shown in Figure 1.11. The Kinect contains a pair of color and depth imaging sensors, which allow three-dimensional viewing, and a standard RGB camera with an overall system sampling rate of approximately thirty frames per second. The combination of multiple sensors and an infrared emitter in fixed locations within a single unit allows detection of object position in three dimensions, provided by the hardware as a depth image map. The Kinect also has motors inside the base of the unit, which

allow the sensors to pan and tilt, thus enabling the system to follow users throughout the capture volume, and integrated microphones for audio-based positioning and speech control of software.

B. SOFTWARE

From the primary depth image output of the Kinect sensor, algorithms allow the software to define prominent skeletal features, such as joint centers, located by interpolation based on a surface map of the body [4]. For the Kinect's original purpose as a video game gesture-based controller, positions of certain features are used to provide the input for games. The Kinect firmware has multiple operating modes, including standing (whole-body detection), seated (torso, upper extremity, and head detection), and both normal range and near mode, which allows the user to be positioned very close to the sensor, thus improving spatial resolution of depth detection for finer movements.

C. BENEFITS AND LIMITATIONS

The Kinect has limitations in motion analysis applications, including differing detection behavior based on color and reflectivity of objects, imprecise edge detection, and accuracy approximately one order of magnitude lower than a Vicon kinematic motion analysis system, with RMS error of 7.7 mm on average versus the calibrated Vicon [5]. In addition, its single-camera design creates difficulty in detecting skeletal motion with outside objects in the capture volume, or in situations when portions of the skeletal structure are occluded by other body parts. The system also generally requires users to be positioned facing the sensor and within specific ranges from the sensor. These limitations will be evaluated in more depth later in this work. The Kinect system contains hardware and software that tracks skeletal position via markerless imaging, which is ideal for easy-to-implement clinical motion analysis. Typical clinical systems are permanent laboratory-based installations that cannot measure kinematics outside the traditional clinical environment, while the Kinect is compact and highly portable. The Kinect

sensor has been evaluated as a portable clinical motion analysis platform and has been shown to be effective in this role [5].

VI. CONCLUSION

There are no inexpensive markerless systems available that quantitatively assess upper extremity motion during standardized task performance. Children with HCP are typically evaluated in performing UE activities, and rehabilitation methods and surgical interventions are common interventions which require precise evaluation of upper extremity function. Evaluation methods are either clinical activity-based, which are easy to administer but lack sensitivity, or kinematic motion analysis, which is precise but difficult and expensive to operate. Modern markerless motion capture technologies such as the Microsoft Kinect have the potential to provide the benefits of motion analysis technology without key limitations of traditional clinical evaluation methods. The purpose of this work is to develop a Kinect-based system capable of tracking motion during administration of the standardized Shriners Hospitals for Children Upper Extremity Evaluation (SHUEE), obtain a characterization of normal subject upper extremity kinematics, and evaluate the system based on its technical capability as a low-cost motion analysis platform and efficacy as a supplement to the SHUEE.

CHAPTER 2: EXPERIMENTAL METHODS AND RESULTS

I. INTRODUCTION

Development of the Microsoft Kinect low cost motion analysis platform includes several key areas of focus. First, software that detects, processes, and records skeletal position data is developed. Next, software is designed to filter and process raw skeletal position data into effective angular kinematics for clinical use and, in the case of cyclic activities, kinematic plots. Then, algorithms are created to use calculated angular kinematics to numerically describe upper extremity performance. Finally, a user interface is developed to allow therapists to select and record activity performance, allowing the evaluation process to occur with activities performed in quick succession. Figure 2.1 demonstrates the overall conceptual design of the system.
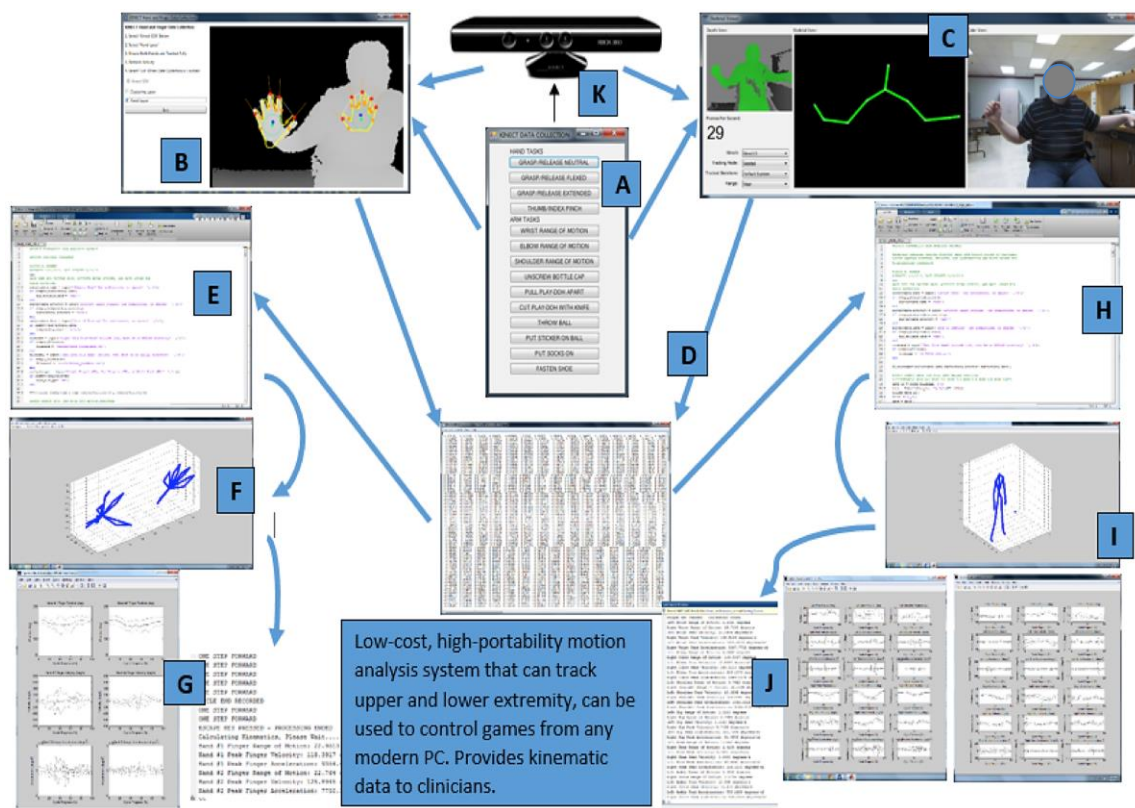
Figure 2.1. Kinect Motion Analysis System – Conceptual Model of System.

The primary user interface (A) allows button selection of Kinect (K) activities to launch the appropriate data collection application, (B) for hand activities and (C) for upper-extremity or whole-body activities. Data from these applications is stored in text files (D) which are then opened in the hand analysis MATLAB software (E) and whole-body analysis MATLAB software (H). The MATLAB software displays skeletal position while allowing the user to advance through time and select the start and end of activity cycles to analyze (F & I). Once selection is complete, the software calculates angular kinematics (angular position, velocity, and acceleration) for all joints and presents the results as kinematic plots and statistical indicators of performance (G & J).

Activities from the SHUEE are adapted to the Kinect platform by resolving the functional limitations of the markerless system with the evaluative intent of SHUEE activities. Similarly, scoring is adapted from the SHUEE through the use of kinematic statistics rather than observed upper extremity performance. The Kinect system is evaluated using an articulating hand model and elbow fixation device to provide indications of system accuracy, inter-trial reliability, and intra-trial precision of finger and elbow angle results. A study is designed to characterize typically developing adolescent subjects performing standardized tasks using the Kinect as compared to SHUEE performance. This study is performed in a laboratory setting with a licensed physical therapist. Twelve typically developing adolescent subjects are tested with both Kinect and SHUEE evaluations to characterize normal population performance and determine correlation between the SHUEE and Kinect system.

Key results obtained through evaluation of the Kinect motion analysis system include results of basic system technical evaluation testing, SHUEE scores for tested subjects, Kinect results for tested subjects, statistical analysis of Kinect and SHUEE results, and a collection of population mean values for standardized activities and algorithm development.

II. SOFTWARE DEVELOPMENT

Software has been developed to allow the Kinect sensor to detect, record, and process upper extremity kinematics during standardized activity performance. Software development details are provided along with pictorial demonstration of the system as seen by a primary user, the therapist. Two primary components are included, with the skeletal tracking and recording component intended for real-time data acquisition during activity performance and the data analysis and display component for post-evaluation processing and interpretation of results.

A. SKELETAL TRACKING AND RECORDING

The Kinect sensor provides a depth image map that is used to detect body surface, while algorithms interpolate joint centers and anatomical landmarks, which are used to determine the instantaneous location of the skeletal structure during movement. To track and record skeletal position experimentally, a front-end interface is used to launch one of two detection algorithms, one an upper extremity system and the other a hand-only system. This interface launches the data collection application, creates a new text file with activity name, date, and time of evaluation, and begins data collection with a single button click. Therapists are able to easily and quickly cycle through all evaluations to minimize required patient evaluation time.
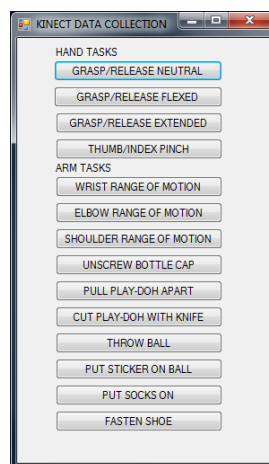
Figure 2.2. Kinect Motion Analysis System – Activity Selection Screen

The skeletal tracking and data recording components are designed to be fast and simple to implement clinically. The user interface (Figure 2.2) allows the therapist to initialize an activity-specific data recording session by clicking the appropriate on-screen button. Then, a graphical interface appears showing real-time upper extremity or hand skeletal tracking display, allowing the therapist to ensure appropriate data is being collected and indicate subject movement corrections in real-time. Throughout operation, data is recorded to text files in the form of 3-D joint center and anatomical landmark coordinates consisting of position within the capture volume. Each data file and data point is time-stamped for future analysis.
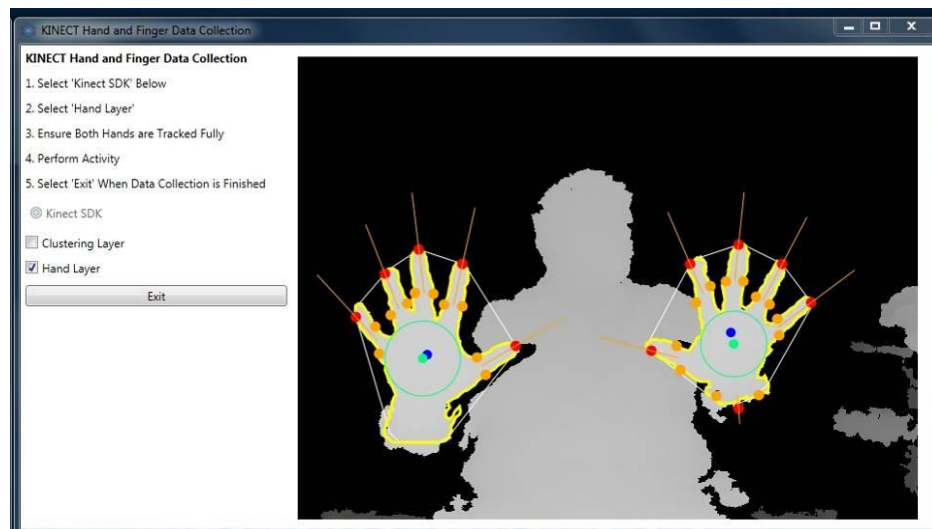
Figure 2.3. Kinect Motion Analysis System – Hand Tracking Skeletal Display
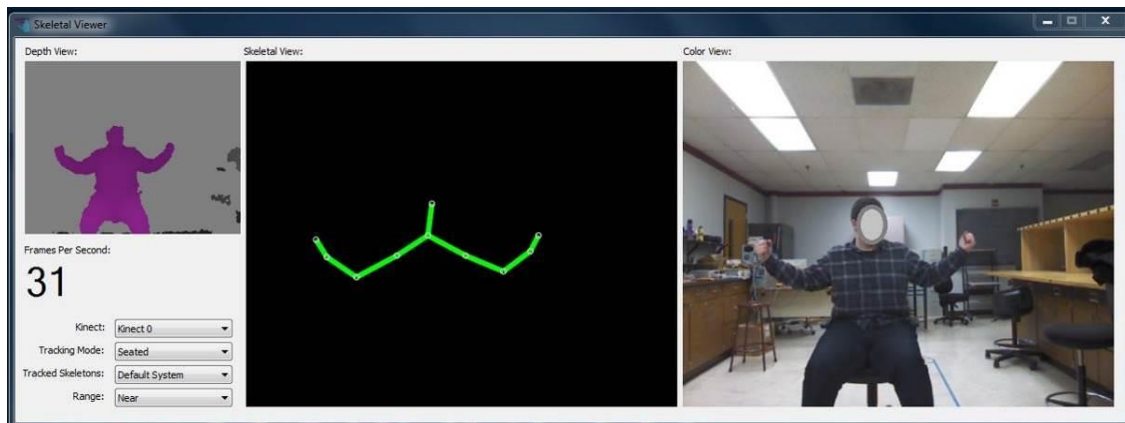
Figure 2.4. Kinect Motion Analysis System – Seated Upper Extremity Tracking Skeletal Display.
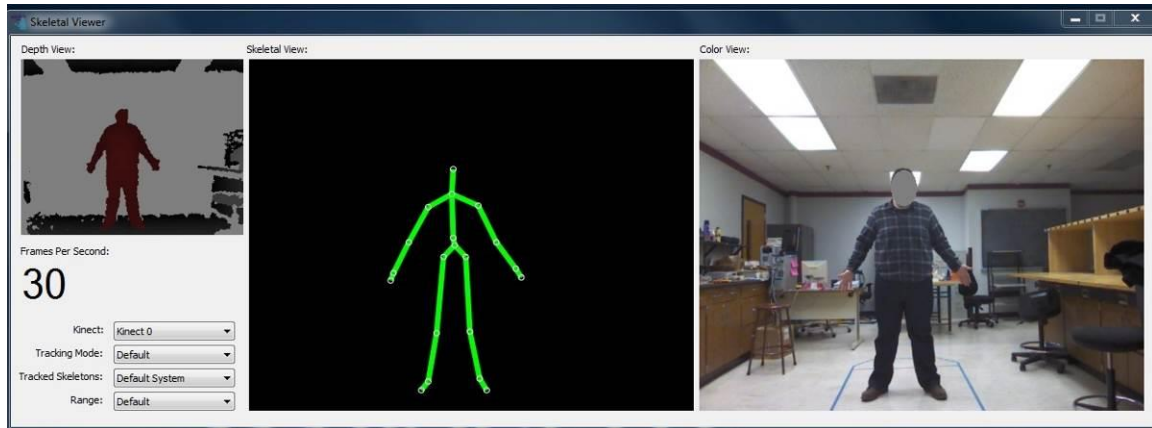
Figure 2.5. Kinect Motion Analysis System – Standing Whole-Body Tracking Skeletal Display.

The data collection software contains two separate algorithms: one for hands and fingers only (Figure 2.3), and a second for upper extremity tracking (Figure 2.4) or whole-body tracking (Figure 2.5). These algorithms employ the Kinect depth sensor, by detecting the outline and depth within the capture volume of the body segments and interpolating estimated joint center locations.

The upper extremity algorithm is an included component of the Microsoft Kinect software development package [4]. The algorithm operates by interpolating skeletal structure based on depth imaging of the body surface and comparing detected structure with typical skeletal arrangement. The detection algorithm itself is included in this software unmodified from the original design created by Microsoft Research, but the software package has been modified to allow real-time recording of skeletal position values expressed as three dimensional coordinates within the capture volume. For the upper extremity, anatomical locations of interest including shoulder joint centers, elbow joint centers, wrist joint centers, base of neck, and head center of mass are recorded throughout testing. The lower extremity model adds spine, pelvis, hip joint centers, knee joint centers, ankle joint centers, and foot centers of mass.

The underlying algorithm used in Kinect skeletal detection of broad upper and lower extremity movements was developed by Microsoft Research and is included within the Kinect firmware and drivers. The algorithm uses depth image data obtained from the Kinect hardware

sensors and processes each frame individually in real time. The body depth image is divided into

31 unique segments encompassing all joints of interest, using a randomized decision forest

method trained based on a large number of random poses and anthropometry to label segments

and interpolate expected skeletal position [53]. The software specifically focuses on joint center

locations or centers of anatomical features, with the detected features shown in Figure 2.6.

Microsoft Research estimates a mean average precision of inferred joint locations relative to

actual joint locations to be 91.4%. Precision varies depending on the joint being studied based on

difficulty in accurate interpolation; for instance, the elbow is highly accurate and precise given

that the arm and forearm are easily defined segments.
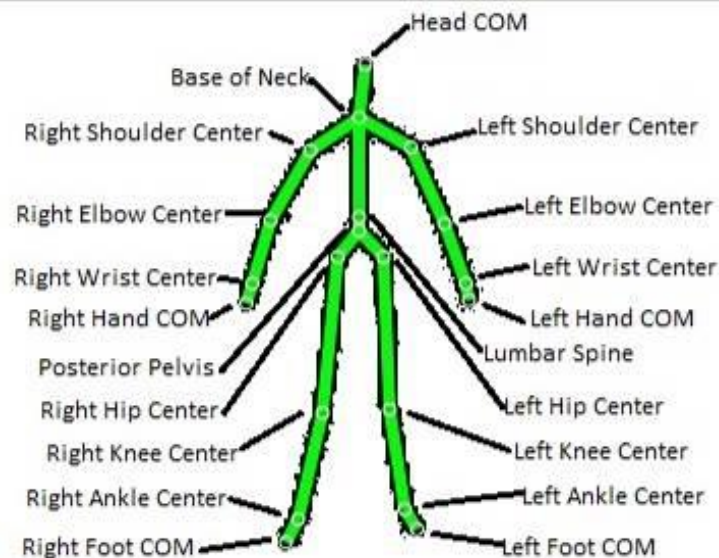
Figure 2.6. UE and Whole-Body Model Detected Features.

The hand tracking algorithm is modified from the CCT NUI open-source system [52], to

include real-time skeletal tracking and data recording with anatomical locations expressed as

three dimensional coordinates within the capture volume. Each hand is tracked at multiple

anatomical landmarks including the finger tips, two sides of each finger at the proximal inter-

phalangeal joint, and the center of the palm, in real time, at a continuous sampling rate of

approximately 30Hz. Detected features are demonstrated in Figure 2.7. These detected

coordinates provide sufficient detail to allow characterization of hand motion, but lack specificity

of individual detection of each joint in the finger, due to limitations in resolution of Kinect depth

image detection, instead providing a single angle for each finger to detect motion quantitatively.

This simplified detection process does not correlate with any specific joint on each finger, but

rather provides an angle that represents overall finger motion, a strategy consistent with the intent

of the system.
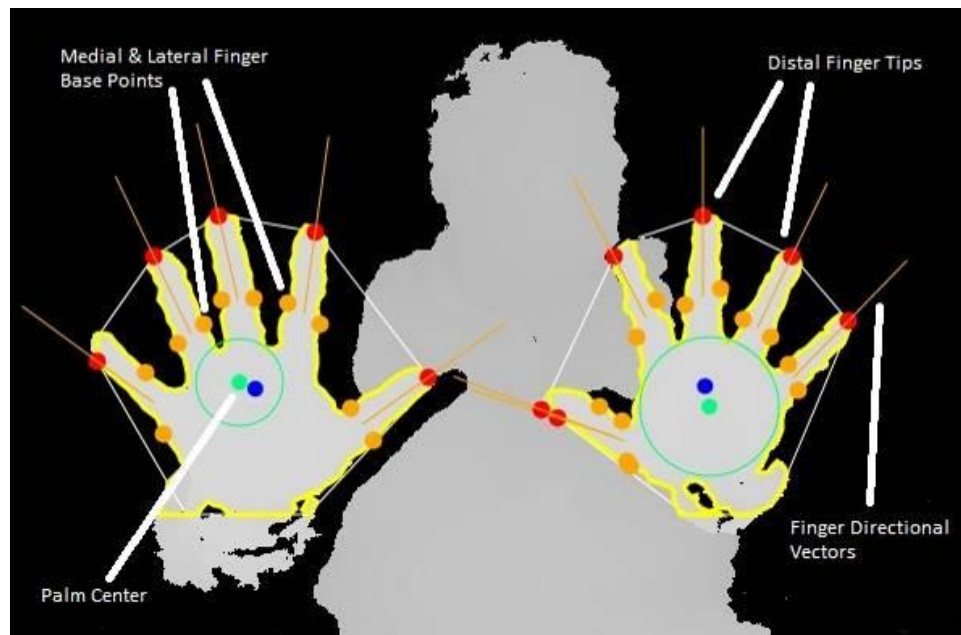
Figure 2.7. Hand Model Detected Features.

B. DATA ANALYSIS AND DISPLAY

The MATLAB-based data analysis software component allows the user to import and

process raw kinematic data collected from testing and calculate angular kinematics for the joints

being studied. This component also displays kinematics in a clinically relevant graphical manner

and calculates important statistics such as joint range of motion.

Once the software has been initialized, the user is asked to input the subject research

identifier, date and time of testing, and activity being studied, implemented using basic MATLAB

I/O (Appendix I, Figure I-1). The raw data is then imported and processed and the user is provided with a graphical display of skeletal position data consisting of the joint center locations and interpolated connecting linkages that represent the skeletal structure. The user can advance through time and select the starting and ending points for each cycle of kinematic testing for cyclic activities or the start and end of testing for non-cyclic activities. Start and end timestamps are then stored for later processing.

This is realized in software through the MATLAB 3-D scatterplot function set, with instruction subsets written to allow keyboard-based control and store timestamps for further analysis based on user selection. An additional function is written to interpolate the simulated skeletal structure based on provided 3D kinematic coordinates. The system is initialized and the user is provided with instructions for viewing skeletal data throughout the test and selection of cycle start and end times (Appendix I, Figure I-2). Once initialized, the function begins detecting user input and uses interpolation techniques to convert 3D joint coordinates into a pseudo-linear 3D skeletal structure, to allow the user to visualize skeletal position throughout the analysis and appropriately select cycle milestones (Appendix I, Figure I-3).

For each time step advanced by the user, the skeletal structure plotting function (Appendix I, Figure I-4) is updated, allowing the user to advance or reverse through frames and visualize the temporal progress of the subject during activity performance, allowing accurate determination of start and end points. Plots represent either the upper extremity alone (example demonstrated in Figure 2.8 below) or the whole body (example in Figure 2.9 below), depending on how data was initially collected by the system. It is possible to use the system to evaluate upper and lower extremity motion simultaneously or upper extremity motion alone. The hand evaluation component (example plot in Figure 2.10 below) is completely separate from the UE or whole-body software component and requires different processing methods based on the collected data. The hand component has multiple evaluation modes, including whole-hand mode,

single-finger mode, or two-finger mode, depending on the specific kinematic focus of the activity being analyzed.
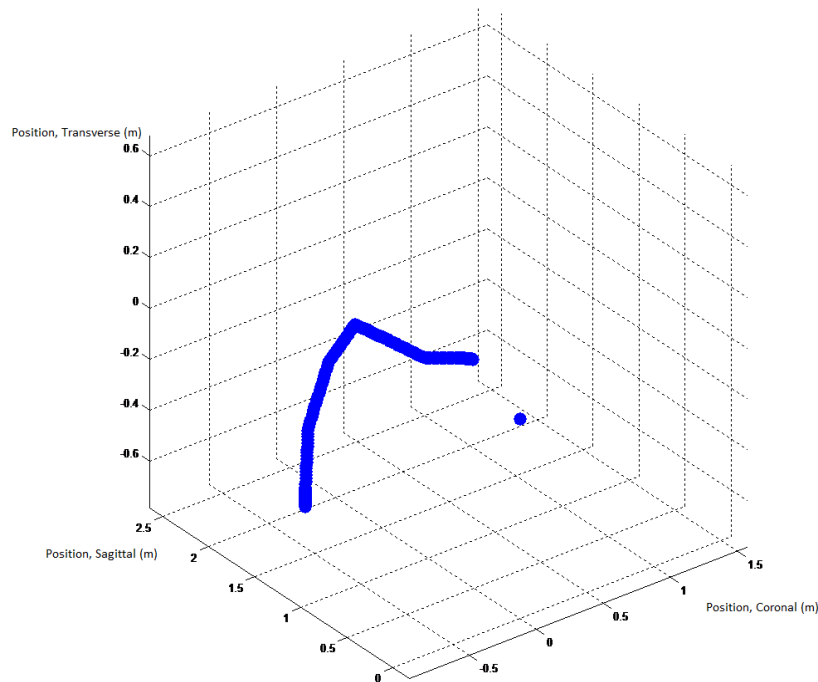
Figure 2.8. Kinect Data Analysis User Interface – Upper Extremity Display.
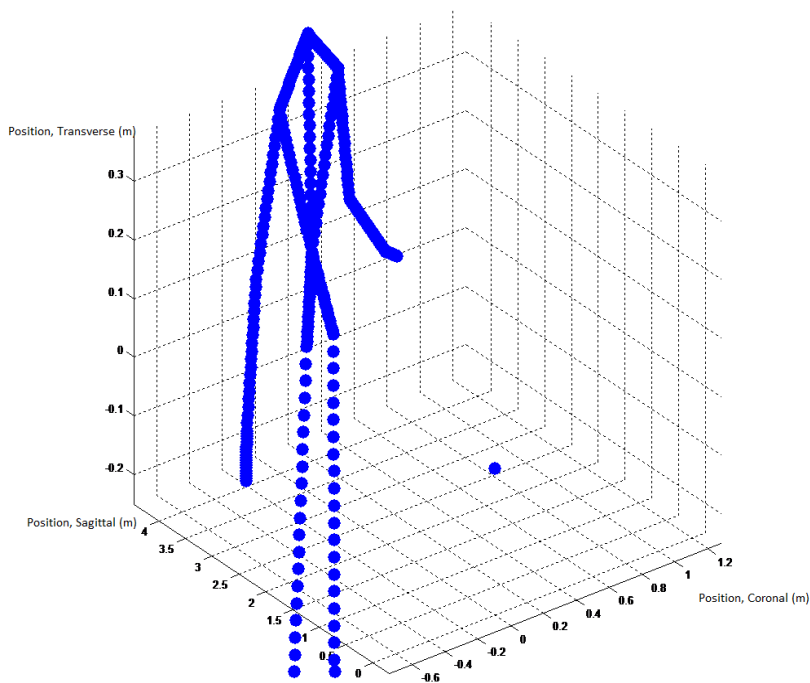
Figure 2.9. Kinect Data Analysis User Interface – Whole-Body Display.
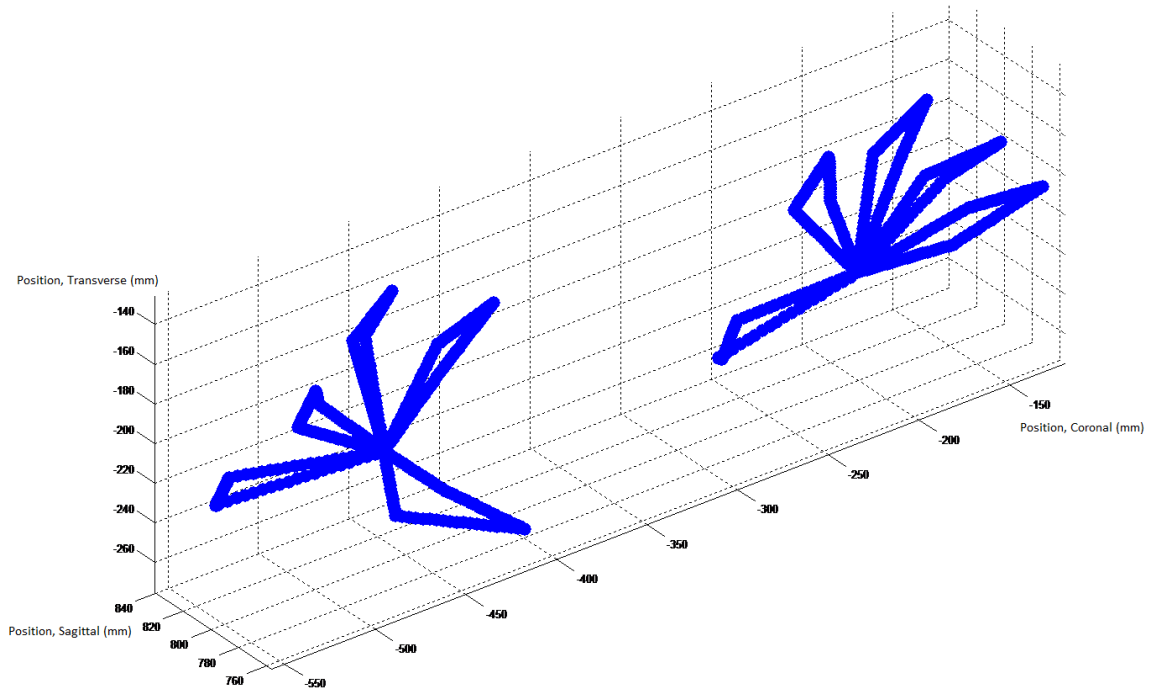
Figure 2.10. Kinect Data Analysis User Interface – Hand Display.

The relatively low sampling rate of the Kinect system at 30Hz can cause significant variability in results, especially with the faster movements of the hand. Filtering is performed to smooth position data and allow for more accurate calculations and display of kinematic performance. A second-order low-pass digital Butterworth filter is implemented in MATLAB (Appendix I, Figure I-5) with a 1.5 Hz cutoff frequency and 30 Hz sampling rate.

Once start and end frames of each cycle have been selected, the software algorithms calculate the joint angles for each joint of interest throughout the evaluation cycle, using an arctangent calculation with dot and cross products (Eq. 2.1), where DIST and PROX are unit vectors representing the segments distal and proximal, respectively, to the joint of interest. Calculations are implemented using MATLAB mathematical functions (Appendix I, Figure I-6).

$$(2.1) \qquad \theta = \arctan\left(\frac{\left|DIST \times PROX\right|}{DIST \bullet PROX}\right) * \frac{180}{\pi}$$

Values are calculated for joint angle throughout each cycle, as determined by previously

selected cycle start and end times. There are certain kinematic limitations to using this method,

such as a lack of planar differentiation in results and discrepancies over larger angular

displacements. The calculated joint angles are then used to determine angular velocity and

acceleration using the first and second order central difference methods, respectively (Eqs. 2.2

and 2.3). These functions calculate the derivative of position data numerically based on leading

and trailing values; dt in each equation represents the time step between subsequent position

values, in the case of the Kinect 1/30 s at 30 Hz.

$$(2.2) \qquad \omega = \frac{d\theta}{dt} = \frac{\theta_{x+1} - \theta_{x-1}}{2 * dt}$$

$$(2.3) \qquad \alpha = \frac{d\omega}{dt} = \frac{d^2\theta}{dt^2} = \frac{\theta_{x+1} - 2\theta_x + \theta_{x-1}}{dt^2}$$

Functions for velocity and acceleration calculations in MATLAB are presented in

Appendix I, Figures I-7 and I-8, respectively. These methods are not intended to correlate with

typical UE kinematic measurements, as determination of actual angular velocity and acceleration

requires accounting for three planes of motion while the calculations presented here simplify each

joint to a single angle. The velocity and acceleration plots and statistics are designed for relative

comparisons.

Cyclic data must then be normalized to cycle progress to ensure multiple averaged cycles

accurately depict true trajectory regardless of cadence of movement. This is implemented in

MATLAB using a linear interpolation function that normalizes data to 101 points, representing

0% to 100% in 1% increments (Appendix I, Figure I-9).

Certain relevant metrics are calculated from kinematic data for each activity, including

range of motion for each joint, peak angular velocity, and peak angular acceleration, calculated in

MATLAB through simple functions (Appendix I, Figure I-10). These statistics are intended to be

used as components to calculate scores that quantify upper extremity kinematics and characterize

normal UE performance or clinical metrics. Algorithms that use joint range of motion, peak angular velocity, and peak angular acceleration will be developed to predict SHUEE scores based on Kinect performance of tasks in future work.

For cyclic activities, angular position, velocity, and acceleration for each joint are plotted against percent completion of cycle for each activity. This provides a graphical depiction of motion quality, and these plots will, in future testing of affected subjects, include experimentally determined normal population mean regions to indicate those portions of the activity cycle with disparities, thus identifying qualitative rehabilitation goals. A MATLAB function plots the mean trajectory and one standard deviation above and below (Appendix I, Figure I-11). Examples of these plots for the hand and upper extremity components, respectively, are shown in Figures 2.11 and 2.12 below.
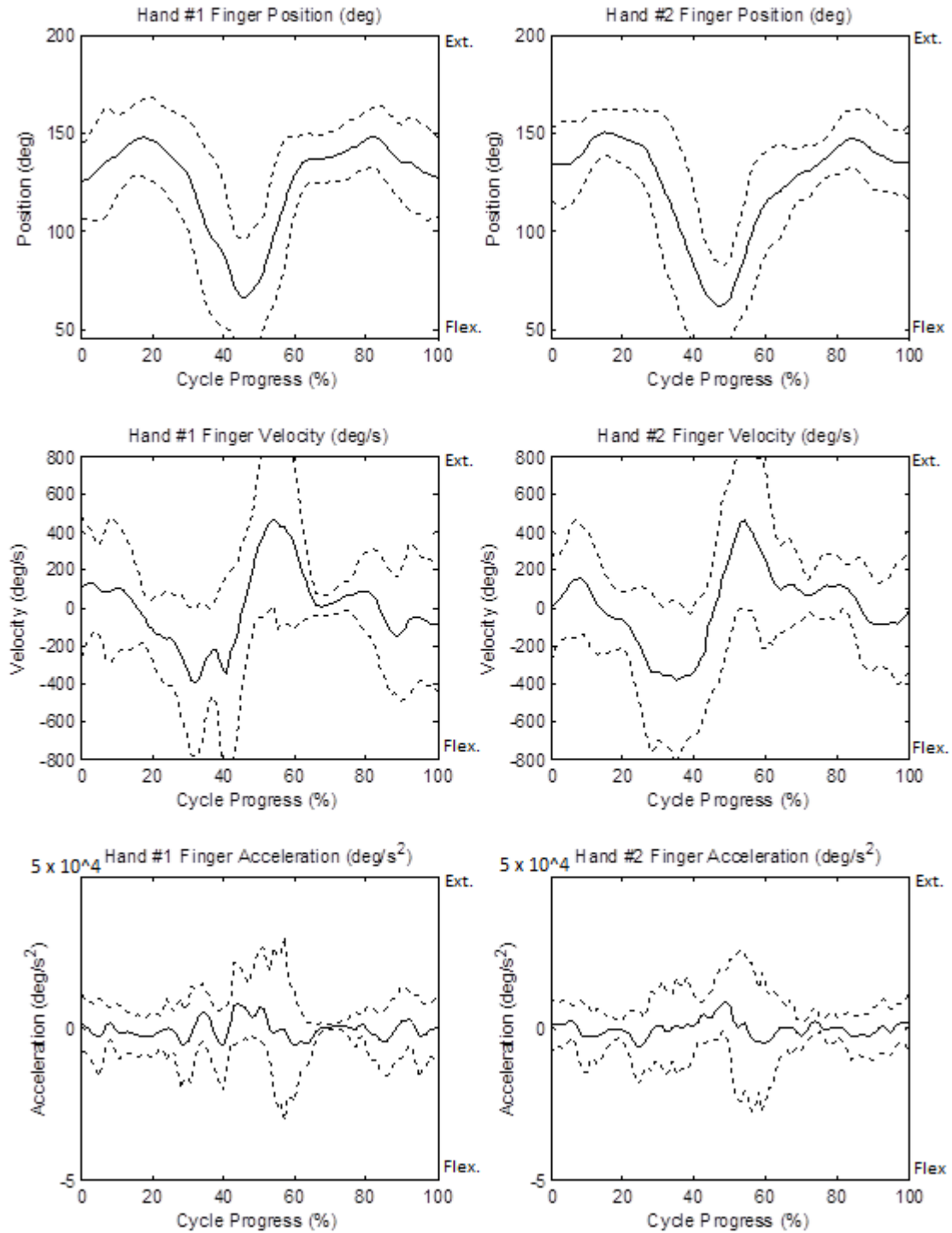
Figure 2.11. Kinect Kinematic Output Display, Grasp/Release Neutral Activity for Single Subject

(solid lines are mean of 10 trials, dashed lines are + 1 standard deviation and − 1 standard
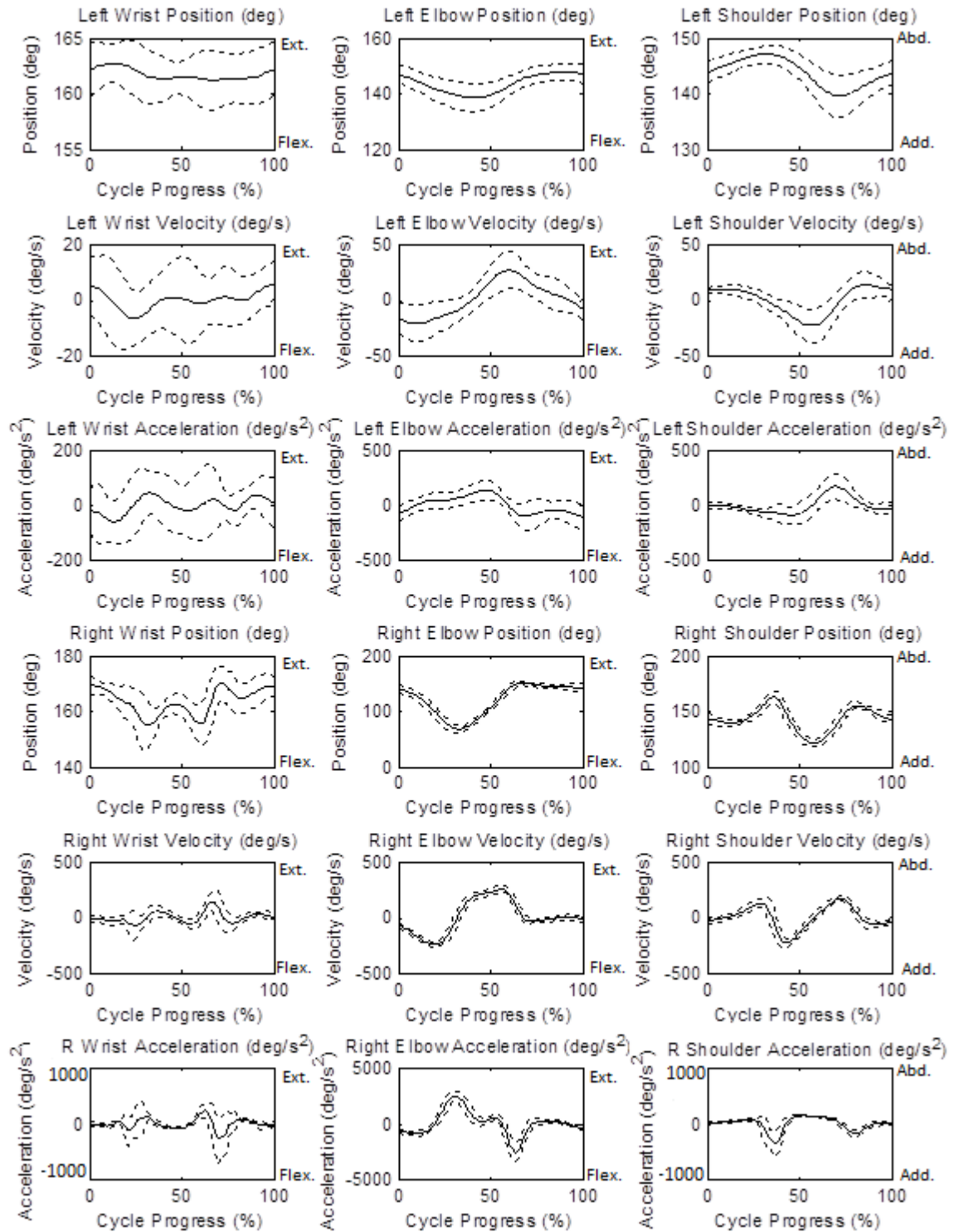
deviation).

Figure 2.12. Kinect Kinematic Output Display, Overhand Ping-Pong Ball Throwing Activity for Single Right-Handed Subject (solid lines are mean of 10 trials, dashed lines are + 1 standard deviation and – 1 standard deviation).

III. TECHNICAL EVALUATION

In order to evaluate the performance and accuracy of the Kinect motion analysis system, a series of laboratory tests are performed. To evaluate the hand component of the system, a flexible anthropomorphic hand model is developed (Figure 2.13), with each finger capable of being individually flexed to and fixed at anatomically appropriate angles.

Figure 2.13. Lab-Developed Anthropomorphic Articulating Hand Model

The hand is captured using the Kinect with fingers simulated at 180 degrees in full extension, at 135 degrees in flexion, and 90 degrees of flexion measured with a protractor (Figure 2.14 below), moved within the hand capture volume, and evaluated using the hand analysis component of the Kinect motion analysis platform for three trials per angle.
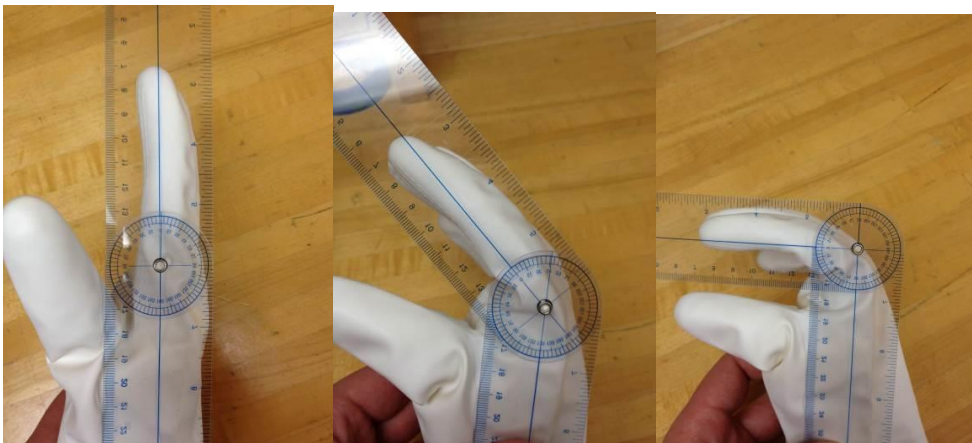
Figure 2.14. Hand Positioning: full extension 180°(left), flexed 135°(center) and flexed 90°(right)

In addition, the hand is rotated in the transverse and sagittal planes in full finger extension, with forearm vertical and wrist neutral, to determine maximum detection angles, to determine the range of forearm pronation/supination and wrist flexion/extension within which the system is able to detect finger position. Detected joint angles are compared statistically to indicate accuracy of angle detection, inter-trial repeatability of the hand system in finger angle detection, and standard deviation within individual trials to indicate level of intra-trial accuracy and detect noise or variability in the system.

To evaluate the broad movements of the upper extremity, the elbow is evaluated using a lab-developed elbow fixation device (Figure 2.15), which is designed to allow adjustment and fixation of elbow angle measured by a protractor, while allowing normal shoulder and wrist movement.

Figure 2.15. Lab-Developed Elbow Fixation Device

The elbow is fixed at measured angles of 180 degrees (full extension), 135 degrees, and 90 degrees (Figure 2.16 below), and moved within the capture volume slowly while kinematics are recorded with the UE analysis component of the Kinect motion analysis platform for three trials per angle.

Figure 2.16. Elbow Positioning at full extension 180° (left), 135° (center), and 90° (right)

Results are processed and statistically compared to indicate accuracy of angle detection and intra-trial and inter-trial repeatability of detected joint angles throughout testing. This comparison is based on mean and standard deviation of hand and elbow angles detected by the Kinect system compared to goniometric measurements of the fixed angles. Results of the hand model evaluation are included in Table 2.1 below. Angles detected by the system using the hand model, with fingers fixed to 180°, 135°, and 90°, demonstrated accuracy (comparison with fixed angle and mean of detected angles) to be highest at full extension (-0.9°) and decreasing with increased flexion (+4.4° at 135° and +8.5° at 90°), with observed decreased precision (increasing standard deviation of detected angles) as finger flexion increases.

Table 2.1. Key Results of Hand Model Technical Evaluation

Fixed Finger Angle	Full Extension 180.0°	135.0° Flexion	90.0° Flexion
Kinect detected angle (Mean ±SD)	179.1°±11.5°	139.4°±12.9°	98.5°±18.4°

Results of the elbow detection study are included in Table 2.2 below. The elbow fixation device fixed to 180°, 135°, and 90° showed detection by the system with precision throughout the elbow range of motion (maximum standard deviation of 5.7%), but with reduced accuracy at full elbow extension (-6.9° at 180°) than with elbow flexed (+2.7° at 135° and +3.5° at 90°). The

elbow joint is also shown to be more precise in detection than the finger joints, as expected based on the limited resolution of the sensor.

Table 2.2. Key Results of Elbow Fixation Device Technical Evaluation

Fixed Elbow Angle	Full Extension 180.0°	135.0° Flexion	90.0° Flexion
Kinect detected angle (Mean ±SD)	173.1°±3.2°	137.7°±5.4°	93.5°±5.3°

Testing with the hand model, mounted on a tripod and rotated away from perpendicular, with the Kinect in the sagittal plane and transverse plane revealed a detection range of ±40° in the sagittal plane and ±45° in the transverse plane (results in Table 2.3 below), significant enough to allow many activities of daily living to be successfully captured using the system, provided the user maintains tracking by ensuring the hand remains within these limits.

Table 2.3. Key Results of Hand Model Detection Range Testing

Hand Detection Plane	Detection Range (from Perpendicular to Kinect)
Sagittal Plane	±40°
Transverse Plane	±45°

See Appendix II for complete details and results of the Kinect system technical evaluation.

IV. ACTIVITY AND SCORING DEVELOPMENT

A. STANDARDIZED UPPER EXTREMITY ACTIVITIES

The intention of the SHUEE is to use activities similar to expected activities of daily living to measure functional upper extremity performance. The activities used for the Kinect analysis are adapted based on the SHUEE, with key changes resulting from functional limitations inherent to the single-camera nature of the Kinect and its simplistic skeletal tracking capability lacking planar differentiation.

Of the activities included in the SHUEE, some are able to be directly reproduced using the Kinect hardware for analysis, and others are not able to be as fully reproduced due to hardware and software limitations. The Kinect system is able to analyze the elbow activities well, and can directly emulate those SHUEE activities, but is unable to detect forearm pronation/supination or thumb/finger activities involving manipulation of objects, since objects may obstruct the imaging system of the Kinect. In addition, the Kinect system cannot detect differentiation in planar motion of the shoulder or wrist, thus limiting reporting of those joints to single-angle. However, simplified activities may be substituted for the activities where objects obstruct the depth sensor, using gestures instead of object manipulation, to ensure accurate and artifact-free skeletal tracking while obtaining data that remains relevant to the SHUEE. Range-of-motion activities in the elbow, wrist, and shoulder have been used to quantify UE kinematics [15] and are included in the Kinect activities described here as a simplified replacement for selected SHUEE activities.

Table 2.4 describes all activities comprising the Kinect evaluation in detail with estimated testing duration, kinematic foci, system setup, and testing protocol. This protocol is used for a normal subject study described in detail below, and represents a comprehensive evaluation of upper extremity function intended for use with children with hemiplegic cerebral palsy.

Table 2.4. Kinect Upper Extremity Activities

Activity & Estimated Testing Time	Kinematic Focus of Activity	Kinect System Mode	Testing Protocol
Grasp/Release Neutral (~1min)	Finger Flexion/Extension with Wrist in Neutral Position	Hand Kinematics Software - Whole-Hand Mode	With the wrist in a neutral position, ask subject to close and open both hands in a repeating pattern to the extent possible. Repeat for 10-20+ cycles and ensure both hands are tracked by software throughout.
Grasp/Release Flexed	Finger Flexion/Extension	Hand Kinematics	With the wrist in a flexed position, ask subject to close and open both hands in a

Activity & Estimated Testing Time	Kinematic Focus of Activity	Kinect System Mode	Testing Protocol
(~1min)	with Wrist in Flexed Position	Software - Whole-Hand Mode	repeating pattern to the extent possible. Repeat for 10-20+ cycles and ensure both hands are tracked by software throughout.
Grasp/Release Extended (~1min)	Finger Flexion/Extension with Wrist in Extended Position	Hand Kinematics Software - Whole-Hand Mode	With the wrist in an extended position, ask subject to close and open both hands in a repeating pattern to the extent possible. Repeat for 10-20+ cycles and ensure both hands are tracked by software throughout.
Thumb-Index Pinch (~1min)	Thumb and Index Finger Flexion/Extension	Hand Kinematics Software - Two-Finger Mode	Instruct subject to hold hands with palms facing Kinect with both hands fully tracked by software, and pinch thumb and index finger in a repeating pattern as if grasping and releasing an object to the extent possible. Repeat for 10-20+ cycles and ensure both hands are tracked by software throughout.
Wrist ROM (~1min)	Wrist Flexion/Extension	Upper Extremity Kinematics Software - Seated or Standing	Instruct subject to hold both arms outward at sides, with palms facing upward, and flex and extend the wrist to the extent possible in a repeating pattern. Repeat for 10-20+ cycles and ensure both arms are tracked fully by the software throughout.
Elbow ROM (~1min)	Elbow Flexion/Extension	Upper Extremity Kinematics Software - Seated or Standing	Instruct subject to hold both arms outward at sides, with palms facing upward, and flex and extend the elbow to the extent possible in a repeating pattern. Repeat for 10-20+ cycles and ensure both arms are tracked fully by the software throughout.
Shoulder ROM (~1min)	Shoulder Abduction/Adduction	Upper Extremity Kinematics Software - Seated or Standing	Instruct subject to hold both arms close to the body at sides, and raise and lower the arm, articulating at the shoulder, to the extent possible in a repeating pattern. Repeat for 10-20+ cycles and ensure both arms are tracked fully by the software throughout.
Unscrew Bottle /Jar Cap (~1.5min)	Wrist Flexion/Extension and Radial/Ulnar Deviation	Upper Extremity Kinematics Software - Seated or	Instruct subject to hold jar with non-dominant hand and unscrew lid, in a repeating cyclic pattern, with dominant hand, repeating for 10-20+ cycles and ensuring that both arms are tracked fully

Activity & Estimated Testing Time	Kinematic Focus of Activity	Kinect System Mode	Testing Protocol
		Standing	throughout (the subject may need to hold the jar out in front of body to ensure accurate tracking).
Pull Play-Doh Apart (~2min)	Wrist Flexion/Extension and Radial/Ulnar Deviation	Upper Extremity Kinematics Software - Seated or Standing	Mold Play-Doh into cylindrical shape and ask subject to pull apart into multiple pieces, holding arms in front of body. Repeat for 10-20+ cycles ensuring that both arms are tracked throughout.
Cut Play-Doh With Knife (~1.5min)	Wrist Flexion/Extension and Radial/Ulnar Deviation	Upper Extremity Kinematics Software - Seated or Standing	Mold Play-Doh into flat circle and instruct subject to cut the circle in a cyclic pattern using a non-reflective butter knife for 10-20+ cycles (i.e. multiple cuts across the chord of the circle), using the dominant hand and ensuring that the arm is tracked fully.
Throw Ball (~1.5min)	Wrist Flexion/Extension and Radial/Ulnar Deviation	Upper Extremity Kinematics Software - Seated or Standing	Instruct subject to throw ping-pong balls into a basket placed next to the Kinect sensor overhand in a cyclic pattern for 10-20+ cycles using the dominant hand, ensuring that the arm is tracked fully.
Place Sticker on Ball (~1.5min)	Elbow Flexion/Extension	Upper Extremity Kinematics Software - Seated or Standing	Place large ball at arm's length from subject and provide subject with a sheet of stickers. Instruct subject to place stickers on ball using dominant hand in a repeating, cyclic pattern for 10-20+ cycles, holding the sticker sheet in non-dominant hand, while ensuring that the arm is tracked fully.
Put Socks On (~2min)	Elbow Flexion/Extension	Upper Extremity Kinematics Software - Seated or Standing	With subject seated and with one shoe and sock removed, instruct subject to put on and remove the sock in a cyclic repeating pattern, returning to upright seated posture between each cycle, while ensuring that both arms are fully tracked throughout the testing. Repeat for 10-20+ cycles.
Fasten Shoe (~2min)	Elbow Flexion/Extension	Upper Extremity Kinematics Software -	With subject seated and with one shoe untied, instruct subject to tie and subsequently untie shoe in a cyclic repeating pattern, returning to upright

Activity & Estimated Testing Time	Kinematic Focus of Activity	Kinect System Mode	Testing Protocol
		Seated or Standing	seated posture between each cycle, while ensuring that both arms are fully tracked throughout the testing. Repeat for 10-20+ cycles.

B. ACTIVITY SCORING METHODS

Scoring the Kinect evaluation activities differs from the SHUEE, with scoring algorithms that use quantitative metrics to approximate SHUEE scores for GRA, DPA, and SFA analyses. Table 2.5 describes the original SHUEE scoring methodology, and the proposed philosophy and implementation of Kinect scoring algorithms. These methods are intended to be used in future work to score performance of children affected with cerebral palsy based on normal subject performance during the same tasks.

Table 2.5. Kinect Scoring based on the SHUEE

Scoring Metric	SHUEE Score Description [2]	Kinect Scoring Philosophy	Kinect Scoring Procedure
Grasp/ Release Analysis (GRA)	Subject evaluated and scored 0-6 based on ability to grasp and release hand in flexed, extended, and neutral wrist conditions (1pt each). Values are divided by 6 to obtain percentage score.	Use finger range of motion for each GRA activity to evaluate grasp and release capability	Subject evaluated by categorizing measured average range of motion of fingers in terms of population normal (normal population mean finger ROM +/- 1 standard deviation), presented as an overall percentage GRA score.
Dynamic Positional Analysis (DPA)	Subject evaluated based on alignment of segments during activities, with scores of 0-3 for each activity. Values for all segments are summed and divided by maximum possible to obtain	Use range of motion for each segment of interest over all activities directed toward that segment to evaluate positioning capability	Subject evaluated by categorizing measured range of motion of each segment of interest (thumb, finger, wrist, elbow, shoulder) by population normal (population mean +/- 1 standard deviation) for that segment to obtain segment scores, which are then averaged to obtain overall DPA score for the

Scoring Metric	SHUEE Score Description [2]	Kinect Scoring Philosophy	Kinect Scoring Procedure
	percentage score.		subject.
Spontaneous Functional Analysis (SFA)	Subject evaluated based on spontaneity of usage using the Modified House Scale, scored 0-5 for each activity. Values for all activities are summed and divided by maximum possible to obtain percentage score.	Use velocity and acceleration for each activity for segment of interest to evaluate spontaneity of motion	Subject evaluated using average peak velocity and peak acceleration values for each activity to categorize performance based on population normal (population mean +/- 1 standard deviation) for each activity, then averaged over all activities to obtain percentage SFA score for subject.

V. CONTROL SUBJECT STUDY

This study protocol (included in full in Appendix III) has been approved by the Institutional Review Board at Marquette University for human subjects testing. Twelve typically developing adolescent subjects, male and female, ages 12 to 17, with no prior or current injury or impairment to upper extremity function, were recruited to participate in this study. A two-sample power analysis using experimentally collected data indicated a minimum sample size of 9. In addition, a previous study designed to indicate reliability of the SHUEE used 11 subjects [2]. Participants and their parent or legal guardian undergo the informed consent and assent process before beginning testing, and subjects are allowed to withdraw from the study at any time.

The SHUEE is performed by subjects as described in its original guidelines [2] and testing is directed by a licensed physical therapist. Subjects perform simple activities of daily living, such as unscrewing a bottle cap, cutting Play-Doh® as a food simulation, throwing a ball, and using toys, utensils, and other objects at the direction of a therapist while being video recorded for later analysis.

The Kinect evaluation follows the SHUEE, with staff providing the subject with instructions and guidance while the Kinect records kinematic position data. Multiple trials of each

activity are performed in succession using the Kinect sensor to obtain an average kinematic trajectory for each activity, a typical procedure in motion analysis studies where a single trial may not provide the resolution needed for quality results. This averaging has the additional benefit of providing a more accurate depiction of movement trajectory, as rather than reporting highest possible performance of the subject during testing, an average is reported that reflects the performance level the subject is capable of consistently achieving across multiple trials.

Following data collection, SHUEE data analysis is performed by the therapist based on video recordings, and a final score is determined for spontaneous functional analysis (SFA), dynamic positional analysis (DPA), and grasp/release analysis (GRA). Kinect data is analyzed using data processing software to calculate values for range of motion, peak velocity, and peak acceleration for each activity. Population mean and standard deviation values are calculated for each task to be used as an indicator of normal performance in future testing of subjects affected with hemiplegic cerebral palsy.

Table 2.6. Results of SHUEE in Normal Subject Study

Measure	n	SHUEE Score (Pts.)	SHUEE Score (%)
Spontaneous Functional Analysis	n=12	45 ± 0	100% ± 0%
Dynamic Positional Analysis	n=12	60 ± 0	100% ± 0%
Grasp and Release Analysis	n=12	6 ± 0	100% ± 0%

All subject participants (n=12) exhibited expected scores, described in Table 2.6, indicating normal upper extremity function during all activities of the SHUEE for all subjects. The resultant lack of deviation in scores present in the SHUEE ordinal scoring system demonstrates the low sensitivity to detect small variations in upper extremity performance that would be expected in a population of varying age and upper extremity activity level like that studied here.

Results of the Kinect-based evaluation including kinematic metrics and trajectory plots are presented in detail in Appendix IV. Additionally, comprehensive statistical analysis of the results was performed to identify key correlation factors for each activity, presented in Table 2.7. The basis for indicating strongly correlated (Pearson correlation coefficient > 0.9) or semi-correlated (Pearson correlation coefficient >0.5) metrics includes statistical evaluation of study results using The CORR Procedure, which is used here to calculate Pearson correlation coefficients, perform logarithmic-scale conversion, and plot inter-variable correlation (comprehensive results in Appendix IV). In addition, the results of statistical analysis are characterized based on the kinematic focus of each activity, with desired kinematic focus a strongly correlated metric for each. As an example, for the wrist range of motion activity dominant and non-dominant wrist ROM are strongly correlated since they are the kinematic foci of the activity, and wrist velocity and acceleration are semi-correlated since they have Pearson correlation coefficients greater than 0.5. These results provide insight into the kinematic metrics that could be used to characterize activity performance efficiently.

Table 2.7. Key Correlation Factors for Kinect Evaluation in Normal Subject Study

Activity	Strongly Correlated Metrics	Semi-Correlated Metrics
Grasp/Release Neutral	Dominant Finger ROM Non-Dominant Finger ROM	Finger Peak Velocity Finger Peak Acceleration
Grasp/Release Flexed	Dominant Finger ROM Non-Dominant Finger ROM	Finger Peak Velocity Finger Peak Acceleration
Grasp/Release Extended	Dominant Finger ROM Non-Dominant Finger ROM	Finger Peak Velocity Finger Peak Acceleration
Thumb-Index Pinch	Dominant Index ROM Dominant Thumb ROM Non-Dominant Index ROM Non-Dominant Thumb ROM	Thumb Peak Velocity Index Peak Velocity Thumb Peak Acceleration Index Peak Acceleration
Wrist Range of Motion	Dominant Wrist ROM Non-Dominant Wrist ROM	Wrist Peak Velocity Wrist Peak Acceleration

Elbow Range of Motion	Dominant Elbow ROM Non-Dominant Elbow ROM	Elbow Peak Velocity Elbow Peak Acceleration
Shoulder Range of Motion	Dominant Shoulder ROM Non-Dominant Shoulder ROM	Shoulder Peak Velocity Shoulder Peak Acceleration
Unscrew Bottle or Jar Cap	Dominant Wrist ROM Dominant Wrist Peak Velocity Dominant Wrist Peak Accel.	Dominant Elbow ROM Dominant Shoulder ROM
Pull Play-Doh Apart	Dominant Wrist ROM Non-Dominant Wrist ROM Dominant Elbow ROM Non-Dominant Elbow ROM Dominant Shoulder ROM Non-Dominant Shoulder ROM	Wrist Peak Velocity Wrist Peak Acceleration Elbow Peak Velocity Elbow Peak Acceleration Shoulder Peak Velocity Shoulder Peak Acceleration
Cut Play-Doh With Knife	Dominant Wrist ROM Dominant Elbow ROM	Dominant Shoulder ROM Dominant Extremity Velocity and Acceleration
Throw Ping-Pong Ball	Dominant Wrist ROM Dominant Elbow ROM Dominant Shoulder ROM	Dominant Extremity Velocity and Acceleration
Place Sticker on Large Ball	Dominant Elbow ROM Dominant Shoulder ROM	Dominant Wrist ROM Dominant Extremity Velocity and Acceleration
Put Socks On or Fasten Shoe	Dominant Elbow ROM Non-Dominant Elbow ROM	Wrist ROM Shoulder ROM

Population mean values are determined through basic statistical evaluation for each activity, presented in Table 2.8, to allow characterization of performance of affected subjects.

Table 2.8. Population Results of Kinect Evaluation for Key Metrics

Activity	**Metric**	**n**	**Population Mean ±SD**
Grasp/Release Neutral	Dominant Finger ROM	n=12	26.50°±10.83°
	Non-Dominant Finger ROM	n=12	31.67°±14.54°
Grasp/Release Flexed	Dominant Finger ROM	n=12	26.87°±16.55°
	Non-Dominant Finger ROM	n=12	35.96°±22.39°

Grasp/Release Extended	Dominant Finger ROM	n=12	27.10°±12.80°
	Non-Dominant Finger ROM	n=12	28.20°±11.80°
Thumb-Index Pinch	Dominant Index ROM	n=12	33.48°±12.97°
	Dominant Thumb ROM	n=12	26.52°±14.56°
	Non-Dominant Index ROM	n=12	36.21°±12.86°
	Non-Dominant Thumb ROM	n=12	28.67°±11.62°
Wrist Range of Motion	Dominant Wrist ROM	n=12	24.27°±12.63°
	Non-Dominant Wrist ROM	n=12	25.07°±9.14°
Elbow Range of Motion	Dominant Elbow ROM	n=12	122.61°±17.54°
	Non-Dominant Elbow ROM	n=12	121.46°±21.75°
Shoulder Range of Motion	Dominant Shoulder ROM	n=12	74.18°±16.69°
	Non-Dominant Shoulder ROM	n=12	77.61°±14.41°
Unscrew Bottle or Jar Cap	Dominant Wrist ROM	n=12	34.10°±8.33°
	Dominant Wrist Peak Velocity	n=12	318.76°/s±122.16°/s
	Dominant Wrist Peak Accel.	n=12	$18136°/s^2 \pm 10152°/s^2$
Pull Play-Doh Apart	Dominant Wrist ROM	n=12	38.18°±22.93°
	Non-Dominant Wrist ROM	n=12	29.35°±15.58°
	Dominant Elbow ROM	n=12	17.45°±8.54°
	Non-Dominant Elbow ROM	n=12	21.99°±9.80°
	Dominant Shoulder ROM	n=12	12.86°±9.71°
	Non-Dominant Shoulder ROM	n=12	16.76°±11.22°
Cut Play-Doh With Knife	Dominant Wrist ROM	n=12	33.41°±18.64°
	Dominant Elbow ROM	n=12	25.41°±16.36°
Throw Ping-Pong Ball	Dominant Wrist ROM	n=12	32.75°±13.94°
	Dominant Elbow ROM	n=12	40.30°±22.24°

	Dominant Shoulder ROM	n=12	21.66°±10.79°
Place Sticker on Large Ball	Dominant Elbow ROM	n=12	45.02°±19.94°
	Dominant Shoulder ROM	n=12	16.89°±7.79°
Put Socks On or Fasten Shoe	Dominant Elbow ROM	n=12	53.30°±24.14°
	Non-Dominant Elbow ROM	n=12	46.38°±19.05°

Population mean kinematics demonstrate the variation detected across the normal population studied. Bimanual, nonsymmetrical activities such as the Pull Play-Doh Apart activity demonstrate differences observed between dominant and non-dominant upper extremities, with the dominant wrist exhibiting greater contribution to the movement. Bimanual symmetric activities such as wrist, elbow, and shoulder range of motion tasks demonstrate similar performance between dominant and non-dominant extremities, as expected for a typically developing population. Results can also demonstrate detection characteristics of the Kinect sensor. For instance, the grasp-release flexed activity shows substantially more standard deviation in results than grasp-release neutral. This is expected since for this activity the hand is placed in a configuration near the detection limit of the sensor.

Appendix IV provides comprehensive results and statistical analysis of the Kinect study.

VI. CONCLUSION

A comprehensive software package has been developed for use with Kinect hardware to detect, record, filter, process, and present upper extremity kinematics for the shoulder, elbow, wrist, and hand during performance of standardized activities of daily living. Technical evaluation of the Kinect-based system has identified the accuracy and precision of hand and arm component detection, and the range for skeletal detection. A study of typically-developing adolescent subjects during standardized performance of activities based on the SHUEE demonstrates the easy-to-operate nature of the Kinect system in a clinical setting relative to the

SHUEE and provides population normal kinematics for measuring performance of individuals with hemiplegic cerebral palsy. The system provides the quantitative benefits of kinematic motion analysis technology together with the ease-of-use of clinical evaluations, thus advancing the effectiveness of clinical evaluation of children with hemiplegic cerebral palsy.

CHAPTER 3: DISCUSSION AND FUTURE DIRECTIONS

I. INTRODUCTION

The Microsoft Kinect motion analysis platform is a low-cost, high-value upper extremity kinematic analysis system, with great potential both as a standalone markerless tracking system to be implemented in clinical and research activities and as a supplemental tool to improve clinical analysis of standardized upper extremity task performance. The system has been evaluated through laboratory technical evaluation procedures using an anthropomorphic hand model and elbow fixation device, and through a normal population subject study of typically-developing adolescents. Results show the Kinect system can accurately detect UE motion, calculate upper extremity kinematics and is easy to use in a clinical evaluation setting. The system provides multiple important benefits and a few limitations in motion tracking capability. There are a number of prospective applications that could benefit substantially from this system and future improvements to it.

II. DISCUSSION OF RESULTS

The Kinect-based upper extremity motion analysis platform has strong potential for clinical use as a cost-effective, highly portable, versatile, markerless skeletal tracking system. The Kinect is extremely cost-effective when compared with typical clinical motion analysis systems, and is available for approximately $100, in stark contrast to the typical cost of a lab-based system, estimated at $100,000 or more. The Kinect also has the advantage of international availability and language compatibility through Microsoft. The Kinect sensor is compact and requires only the Kinect and a Windows PC for operation. Unlike most advanced motion analysis systems that require significant computing power to operate, the Kinect will effectively operate using almost any modern Windows-based PC.

A significant advantage of the Kinect system is its ability to track skeletal motion using imaging alone, eliminating the tedious application of markers to subjects. This has multiple benefits, including increased patient comfort, decreased preparation time, and enhanced usability outside of the traditional clinical environment. In addition, markerless systems remove the possibility that markers may artificially interfere with upper extremity motion and increase versatility of the system, while reducing the training requirements of clinicians for marker placement procedures.

Technical evaluation of the system using lab-developed hand simulation and elbow fixation devices revealed key findings regarding the capabilities of the Kinect system. The broad movements of the elbow demonstrated more precision in detection than the finer movements of the hand, a result expected due to the limited resolution of the system. Detection accuracy when comparing Kinect-detected and goniometric measurements is significant enough to allow differentiation between angles of the joints, and provide useful kinematic data for clinical decision-making. With other work indicating the Kinect maintains approximately one order of magnitude less precision than typical lab-based systems such as the Vicon system but similar accuracy [5], the results obtained here agree with that assessment, indicating higher standard deviation of detected angles in some situations, such as flexed finger angles, and accuracy issues in some situations, such as fully extended elbow detection. Overall, the system is able to produce reliable and accurate kinematics, with a tradeoff of increased ease-of-use through markerless detection for approximately one order of magnitude reduction in resultant precision.

Comprehensive evaluation of the Kinect system was performed with a sample of 12 typically developing adolescents, using activities based on the SHUEE. The typically developing participants exhibited SHUEE scores of 100%±0%, with no sensitivity in the evaluation to detect small differences in UE performance. The Kinect system detected kinematics for the current sample that indicate a wider range of observed performance, thus indicating increased sensitivity of the system to UE behavior. Statistical evaluation identified key correlated metrics for each

activity and population normal values for each, which provide a basis for evaluation of affected subjects in future work.

The Kinect-based evaluation was nearly as easy to use for the therapist and easy to perform for the subject as the SHUEE, with differences in protocol necessary to allow effective kinematic tracking. Subjects enjoyed observing the live on-screen skeletal tracking while they performed activities, and exhibited an overall positive reaction to the system, suggesting that the system would be clinically viable and able to maintain the attention of patients during evaluation procedures.

The SHUEE can be improved clinically through the use of versatile upper extremity markerless motion analysis platforms without placing additional burdens on patients or therapists. The Kinect system accomplishes these improvements through the addition of quantitative, objective kinematic data acquired from markerless skeletal tracking, increased speed and repeatability of clinical evaluation by removing subjective components, and improved ability to monitor multiple joints simultaneously to observe trends in multi-joint coordination or neuromotor compensatory strategies.

The SHUEE attempts to provide an accurate quantitative clinical measurement of upper extremity function, but has room for improvement, even though intra-observer and inter-observer validity has been shown [2]. The addition of measured, quantitative kinematic data can provide clinicians with increased confidence in patient response to interventions through increased sensitivity of the system to detect kinematic change.

Currently, the SHUEE requires two components: the initial testing while video recording the subject and secondary analysis of the recordings by therapists. The Kinect system operates similarly, with a data recording and data analysis phase. However, data analysis is simplified since the therapist need only select starting and ending points for trials, and scoring and reporting of results is done automatically and objectively by the software. This improves data processing speed and removes subjective scoring from the process, while reducing training required for

therapists to recognize and score impairment based on established ordinal scales. Quantitative kinematic data is included in the scoring algorithm to provide a continuous scale for analysis rather than ordinal categorization of performance, thus increasing resolution of scoring algorithms and overall sensitivity of the system.

The SHUEE video recording focuses on a specific joint for each activity. Since many activities require multi-joint coordination, the Kinect system has the advantage of recording all joints simultaneously, allowing the therapist to observe patterns in a larger scope. Kinematic plots display shoulder, elbow, and wrist data together, thus allowing visual indications of multi-joint coordination or motor compensation strategies typical in HCP task performance. Clinicians are therefore receiving data that is more precise and more comprehensive than typical clinical evaluation protocols would provide.

Limitations of the Kinect system for upper extremity analysis include single-angle reporting of the shoulder, wrist, and fingers, a lack of rotational detection of the forearm and shoulder in the transverse plane, and difficulties caused by obstruction of the anatomy by objects used during testing. Single-angle reporting also causes significant loss of accuracy when calculating velocity and acceleration values, which generally require three planes of analysis for quality results; the velocity and acceleration values provided by the Kinect-based system developed and studied here are intended for relative comparisons only. Further, due to the markerless nature of the system, there is significant noise in locations of detected anatomical features and with use of props during simulation of ADL, which can be mitigated through analysis and averaging of multiple cycles of activities, as well as filtering methods included in the software package. Numerous potential areas of application exist for the Kinect motion analysis system that may benefit from a high-value portable markerless upper extremity evaluation package.

Forearm pronation and supination has been shown to be a significant component of UE motion deficiency in individuals with HCP [28], so lack of detection represents a significant

limitation of the Kinect system. Further, the system cannot detect rotation of the arm or forearm and thus is unable to differentiate between shoulder planar motion and wrist planar motion, instead providing a single joint angle for each, complicating scoring procedures and activity selection relative to the SHUEE. Tracking hands in flexed-wrist grasp-release activity performance results in tracking interference with the forearm, reducing accuracy of this activity compared to grasp-release neutral and extended activities. Further, large or reflective objects have been observed to cause irregularities in data or tracking dropout during task performance, requiring activity or device modification to ensure appropriate data collection. For instance, utensils used in certain activities were covered in non-reflective tape to mitigate tracking irregularities.

At the time of this writing, the second generation of Kinect hardware technology has been announced by Microsoft but not yet released for research use. Specifications of the system indicate significantly higher resolution, higher frame rate, and integrated capability to detect rotation of upper extremity segments. Thus, most of the functional limitations of the current system are expected to be resolved in future developments, with the objective of providing an even more reliable and accurate system for UE evaluation.

III. FUTURE RESEARCH DIRECTIONS

This work focuses on using the Kinect to collect data for motion analysis, ignoring the fact that the Kinect was designed as a gaming control system. There has been significant interest in the application of consumer gaming technology to clinical rehabilitation, and the Kinect offers the potential for simultaneously providing therapeutic intervention to patients with HCP through targeted video gaming and obtaining key measures of kinematic performance improvement to continue therapy goals.

Using video game technology has been shown to facilitate goal attainment in individuals with HCP by incorporating movements in intended directions or perceived motion deficits while

concurrently participating in enjoyable and motivational video gaming platforms [6]. Active video games increase physical activity levels and encourage repetitive UE movements, which stimulates neural plasticity [7] and contributes to functional recovery through enhanced motivation and cortical reorganization [8] in patients with HCP. The involvement of children in the therapeutic design processes can enhance compliance, and video game designs that are enjoyable for the participants and available in the home environment can provide substantial benefits to therapeutic recovery [14] when combined with knowledge of kinematic deficiencies and optimized treatment strategies. Video games have been studied extensively as clinical rehabilitation tools, and have been shown to be effective in positively influencing physical therapy outcomes [38].

A future system using the Kinect proposes to integrate motion analysis hardware and software advances discussed previously with gaming and therapy goal integration to provide a comprehensive system. It would allow physical therapists to design games tailored to specific therapy goals based on standardized task performance deficiencies, provide games to patients in clinical or home settings using a low-cost and high-portability system, and obtain detailed kinematic performance and patient usage evaluations from the system. The system would be quite versatile in application, both in terms of customizability in usage and variety of patient populations.
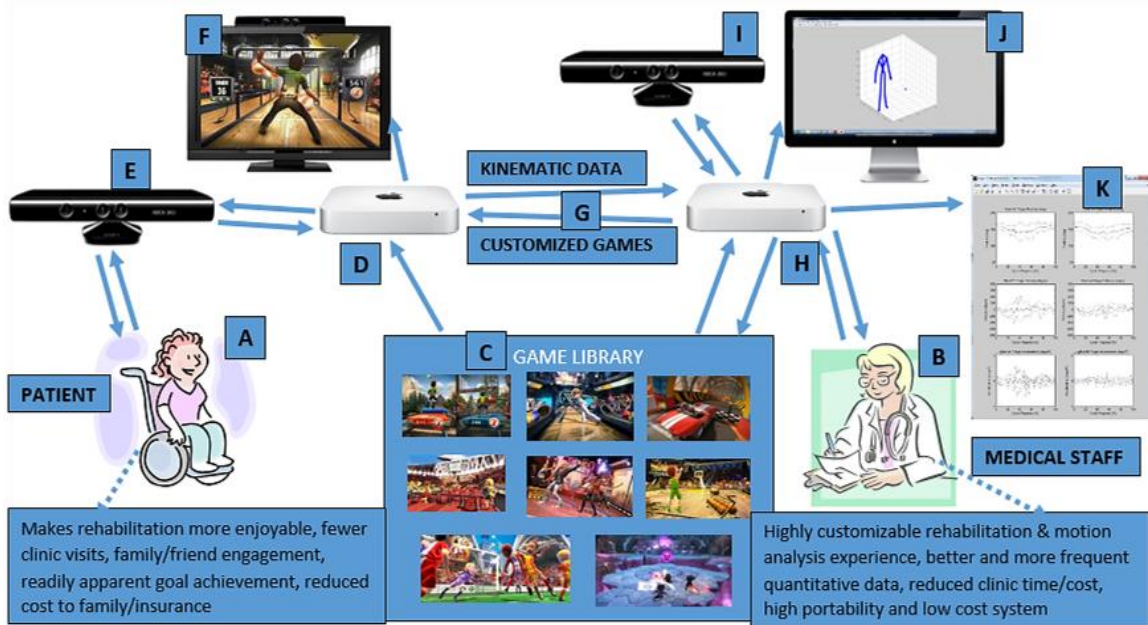
Figure 3.1. Kinect Motion Analysis System – Proposed Model for Integrated Kinect System.

As demonstrated in Figure 3.1 above, future development centers on the two primary users of the Kinect system, the participant (A), who uses the system as enjoyable rehabilitation therapy, and the rehabilitative staff (B), who participate in the design and selection of games (C) that simultaneously offer both rehabilitative exercise and quantitative feedback. The participant's computer (D) interfaces with a Microsoft Kinect sensor (E) and displays games on a standard television or computer monitor (F). The therapist's computer (H) interfaces with the participant's computer either remotely (G) or through programming at the clinic, and interfaces with an additional Kinect sensor (I) for game development and testing as well as interactive participant-therapist gameplay, and a monitor (J) for monitoring results, including quantitative kinematic data (K) valuable to clinicians for gauging participant usage and rehabilitation progress. Customization potential of the game library is unlimited, allowing clinical specialists to work with engineers to design games that achieve rehabilitation goals and provide quantitative information specific to the capabilities of involved participant populations, yielding a system that is functionally adaptable and accessible to a variety of participants (age, activity level, etc.).

In addition to its application as a standardized UE task evaluation system or potential as a clinical rehabilitation platform, the Kinect has been shown to have utility as a standalone clinical motion analysis platform. In this role, the Kinect could be applied to many situations where more complex lab-based systems are difficult to implement, such as low-budget clinics in developing countries, situations where portability would be an asset, and for applications where its markerless operation would reduce setup time and training requirements for system configuration and marker placement.

IV. CONCLUSION

In order to improve standardized task evaluation in individuals with HCP, a new motion analysis platform using the Kinect was developed, including skeletal tracking and kinematic evaluation of hand and arm motion. The system is shown through laboratory technical evaluation to be accurate and reliable in determining UE joint angles, and through a comparative study with the SHUEE to be accurate, reliable, and simple to operate clinically in evaluation of UE performance in standardized clinical tasks. Benefits of the platform include its low cost, high portability, and markerless operation compared with typical clinical systems. Limitations include lack of detection of certain motions of the arm and hand and issues with object obstruction. These issues are expected to be resolved in the forthcoming second generation of Kinect hardware. Future directions of this project will improve its technical capabilities as a motion analysis platform and expand the system to include both adaptive gaming strategies and motion analysis to form an integrated therapeutic platform for rehabilitation of patients with hemiplegic cerebral palsy.

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APPENDIX I: SELECTED CODE

```matlab
function [ newsubjectdata ] = PLOTTER3D( subjectdata )
%PLOTTER3D - THIS FUNCTION PLOTS KINECT POSITION DATA FOR THE ENTIRE
%TRACKED SKELETON, ALLOWS THE USER TO MOVE TIME FORWARD AND BACKWARD USING
%THE ARROW KEYS, AND ALLOWS THE USER TO SELECT CYCLE START/END TIMES (START
%OF CYCLE IS UP ARROW, END OF CYCLE IS DOWN ARROW.  THE FUNCTION OUTPUTS
%THESE START/END TIMES FOR FURTHER ANALYSIS.
%JACOB RAMMER
display('PRESS SPACEBAR TO BEGIN PLOTTING, USE LEFT/RIGHT ARROW KEYS TO');
display('MOVE THROUGH TIME, USE UP ARROW TO MARK CYCLE START AND DOWN');
display('ARROW TO MARK CYCLE END, PRESS ESCAPE TO EXIT PLOT');
```

Figure I.1. MATLAB Function for Cycle Selection (Excerpt – Function Initialization)

```matlab
for i=1:length(subjectdata.timestamp);
    for j=1:length(subjectdata.timestamp);
        while k==0;
        %val=double(get(f,'CurrentCharacter'));%28=L_arrow, 29=R_arrow,
        %30=UP_arrow, 31=down_arrow, 27=escape, 32=spacebar
            w = waitforbuttonpress;
            if w
                val = double(get(gcf, 'CurrentCharacter'));
                if val==27;
                    k=1;
                    display('ESCAPE KEY PRESSED - PROCESSING ENDED');
                    close all
                elseif val==32;
                    %plot first data point
                    display('PLOTTING COMPLETED');
                    i=i;
                elseif val==28;
                    %plot step backward
                    display('ONE STEP BACKWARD');
                    i=i-2;%STEP SIZE
                elseif val==29;
                    %plot step forward
                    display('ONE STEP FORWARD');
                    i=i+2;%STEP SIZE
                elseif val==30;
                    %record timestamp in milestones.start
                    display('CYCLE START RECORDED');
                    subjectdata.events(j,1)=subjectdata.timestamp(i);
                    val=0;
                elseif val==31;
                    %record timestamp in milestones.end
                    display('CYCLE END RECORDED');
                    subjectdata.events(j,2)=subjectdata.timestamp(i);
                    j=j+1;
                    val=0;
```

Figure I.2. MATLAB Function for Cycle Selection (Excerpt – User Control)

```
function [ SEGMENT ] = INTERP_SEG( DISTAL, PROXIMAL )
%This function interpolates points between joints to allow more effective
%visual plotting - Jacob Rammer
SEG(1,:)=PROXIMAL(1,:);
SEG(2,:)=DISTAL(1,:);
step=19;
if SEG(1,1)==0 & SEG(1,2)==0 & SEG(1,3)==0;
    SEGMENT=zeros(20,3);
elseif SEG(2,1)==0 & SEG(2,2)==0 & SEG (2,3)==0;
    SEGMENT=zeros(20,3);
else
xrange=SEG(2,1)-SEG(1,1);
yrange=SEG(2,2)-SEG(1,2);
zrange=SEG(2,3)-SEG(1,3);
xstep=xrange/step;
ystep=yrange/step;
zstep=zrange/step;
SEGMENT(1,:)=SEG(1,:);
for i=1:step;
    SEGMENT(i+1,1)=SEG(1,1)+i*xstep;
    SEGMENT(i+1,2)=SEG(1,2)+i*ystep;
    SEGMENT(i+1,3)=SEG(1,3)+i*zstep;
end
end
subjectdata.lhandseg=INTERP_SEG(subjectdata.l_hand(i,:),subjectdata.l_wrist(i,:));
subjectdata.rhandseg=INTERP_SEG(subjectdata.r_hand(i,:),subjectdata.r_wrist(i,:));
subjectdata.lforearm=INTERP_SEG(subjectdata.l_wrist(i,:),subjectdata.l_elbow(i,:));
subjectdata.rforearm=INTERP_SEG(subjectdata.r_wrist(i,:),subjectdata.r_elbow(i,:));
subjectdata.larm=INTERP_SEG(subjectdata.l_elbow(i,:),subjectdata.l_shoulder(i,:));
subjectdata.rarm=INTERP_SEG(subjectdata.r_elbow(i,:),subjectdata.r_shoulder(i,:));
subjectdata.lshouldseg=INTERP_SEG(subjectdata.l_shoulder(i,:),subjectdata.shoulder_center(i,:));
subjectdata.rshouldseg=INTERP_SEG(subjectdata.r_shoulder(i,:),subjectdata.shoulder_center(i,:));
subjectdata.spineseg=INTERP_SEG(subjectdata.spine(i,:),subjectdata.shoulder_center(i,:));
subjectdata.lshouldtospine=INTERP_SEG(subjectdata.spine(i,:),subjectdata.l_shoulder(i,:));
subjectdata.rshouldtospine=INTERP_SEG(subjectdata.spine(i,:),subjectdata.r_shoulder(i,:));
```

Figure I.3. MATLAB Function for Cycle Selection (Excerpt – Segment Interpolation)

```
f=scatter3(PD(:,1),PD(:,3),PD(:,2),120,'filled');
xlim([xlow xhi])
ylim([ylow yhi])
zlim([zlow zhi])
axis square
val=0;
```

Figure I.4. MATLAB Function for Cycle Selection (Excerpt – 3D Skeletal Display)

```
%FILTER COLLECTED POSITION DATA FOR ALL ANATOMICAL FEATURES
cutoff=1.5;
samplerate=30;
Wn=cutoff/(samplerate/2);
[B,A]=butter(2,Wn);

subjectdata.l_hand(:,1) = filtfilt(B,A,subjectdata.l_hand(:,1));
subjectdata.l_hand(:,2) = filtfilt(B,A,subjectdata.l_hand(:,2));
subjectdata.l_hand(:,3) = filtfilt(B,A,subjectdata.l_hand(:,3));
```

Figure I.5. MATLAB Function for Low-Pass Filtering (excerpt)

```
function [ ANGLES ] = CALC_ANGLE( JOINT, PROX, DIST )
%CALC_ANGLE - THIS FUNCTION CALCULATES THE JOINT ANGLE BASED ON POSITION
%DATA FROM THE JOINT OF INTEREST, THE JOINT PROXIMAL, AND THE JOINT DISTAL
%JACOB RAMMER
%for j=1:length(JOINT);
    LW2H=(DIST-JOINT)./norm(DIST-JOINT);
    LW2E=(PROX-JOINT)./norm(PROX-JOINT);
    ANGLES=(atan2(norm(cross(LW2H,LW2E)),dot(LW2H,LW2E)))*(180/pi);
end
```

Figure I.6. MATLAB Function for Simple Joint Angle Calculation

```
function [ VELOCITY ] = CALC_VELOCITY( POSITION )
%THIS FUNCTION CALCULATES THE ANGULAR VELOCITY FOR A CYCLE OF KINECT DATA
%USING THE CENTRAL DIFFERENCE METHOD
%JACOB RAMMER

%SET INCREMENT (FOR KINECT 30HZ = 1/30)
I=1/30;

VELOCITY=(POSITION(3)-POSITION(1))/(2*I);

end
```

Figure I.7. MATLAB Function for Angular Velocity Calculation

```
function [ ACCEL ] = CALC_ACCEL( POSITION )
%THIS FUNCTION CALCULATES THE ANGULAR ACCELERATION FOR A CYCLE OF KINECT
%DATA USING THE SECOND ORDER CENTRAL DIFFERENCE METHOD
%JACOB RAMMER

%SET INCREMENT (FOR KINECT 30HZ = 1/30)
I=1/30;

ACCEL=(POSITION(3)-2*POSITION(2)+POSITION(1))/(I^2);

end
```

Figure I.8. MATLAB Function for Angular Acceleration Calculation

```
function [ OUTPUT ] = NORMALIZE( INPUT )
%THIS FUNCTION NORMALIZES INPUT CYCLES OF POSITION, VELOCITY, AND
%ACCELERATION DATA TO PERCENT OF CYCLE FOR PLOTTING ANALYSIS
%JACOB RAMMER

x=linspace(1,size(INPUT,2), size(INPUT,2));

xx=linspace(1, x(size(x,2)), 101);

for i=1:size(xx,2)
    OUTPUT(i)=interp1(x, INPUT, xx(i));
end
```

Figure I.9. MATLAB Function for Cycle Normalization

```
%CALCULATE IMPORTANT STATISTICS (SHOULDER AB/AD, FLEX/EXT, INT/EXT; ETC.)
%WRIST RANGE OF MOTION, PEAK VELOCITY, PEAK ACCELERATION
ROM.l_wrist.max=max(subjectdata.l_wrist_angle_meansd(:,2));
ROM.l_wrist.min=min(subjectdata.l_wrist_angle_meansd(:,2));
ROM.l_wrist.ROM=ROM.l_wrist.max-ROM.l_wrist.min;
display(['Left Wrist Range of Motion: ' num2str(ROM.l_wrist.ROM) ' degrees'])
peakvel.l_wrist=max(abs(subjectdata.l_wrist_velocity_meansd(:,2)));
display(['Left Wrist Peak Velocity: ' num2str(peakvel.l_wrist) ' degrees/s'])
peakacc.l_wrist=max(abs(subjectdata.l_wrist_accel_meansd(:,2)));
display(['Left Wrist Peak Acceleration: ' num2str(peakacc.l_wrist) ' degrees/s2'])
```

Figure I.10. MATLAB Function for Calculation of Key Kinematic Metrics (excerpt)

```matlab
%first plot group: upper extremity kinematics

figure('Name','Upper Extremity Kinematics');
set(gcf, 'units','normalized','outerposition',[0 0 .4 1]);
subplot(6,3,1); %left wrist position
PLWP_M=subjectdata.l_wrist_angle_meansd(:,2);
PLWP_L=subjectdata.l_wrist_angle_meansd(:,1);
PLWP_H=subjectdata.l_wrist_angle_meansd(:,3);
plot(0:100,PLWP_M,'-k',0:100,PLWP_L,':k',0:100,PLWP_H,':k');
title('Left Wrist Position (deg)');
xlabel('Cycle Progress (%)');
ylabel('Position (deg)');
```

Figure I.11. MATLAB Function for UE Kinematic Plotting (excerpt)

APPENDIX II: COMPREHENSIVE RESULTS OF TECHNICAL EVALUATION

TEST 1: ELBOW AT FULL EXTENSION
KINEMATIC FOCUS: Elbow detection accuracy and precision in fully extended position
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: With the elbow fixed in full extension (180°) using elbow fixation device, subject moves arm throughout the capture volume for 10 trials while detected elbow angle is recorded.
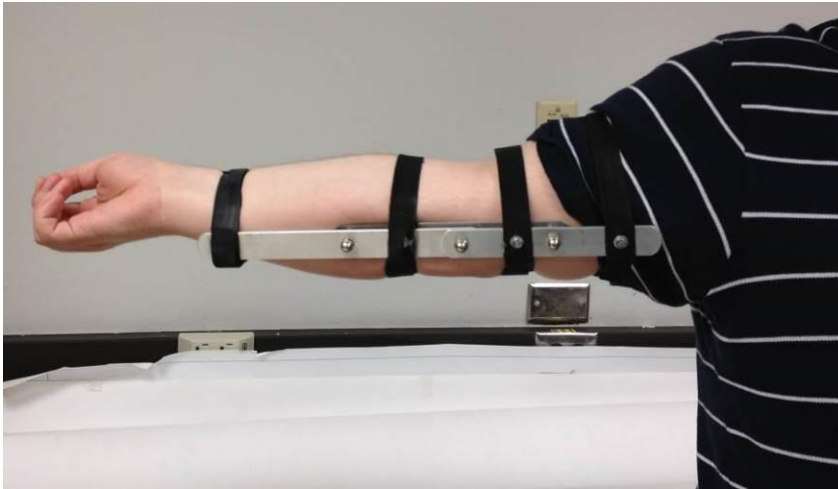
Figure II.1. Testing Configuration

Table II.1. Kinect-Detected Parameters for Exemplar Subject, Elbow at Full Extension (180°)

Trial	Detected Value
Trial #1	171.9°±3.6°
Trial #2	170.6°±3.8°
Trial #3	174.6°±2.7°
Trial #4	172.6°±3.3°
Trial #5	171.1°±1.9°
Trial #6	174.3°±1.3°
Trial #7	174.6°±2.4°
Trial #8	174.9°±2.1°
Trial #9	173.1°±2.9°
Trial #10	173.5°±3.1°
Average of All Trials	**173.1°±3.2°**
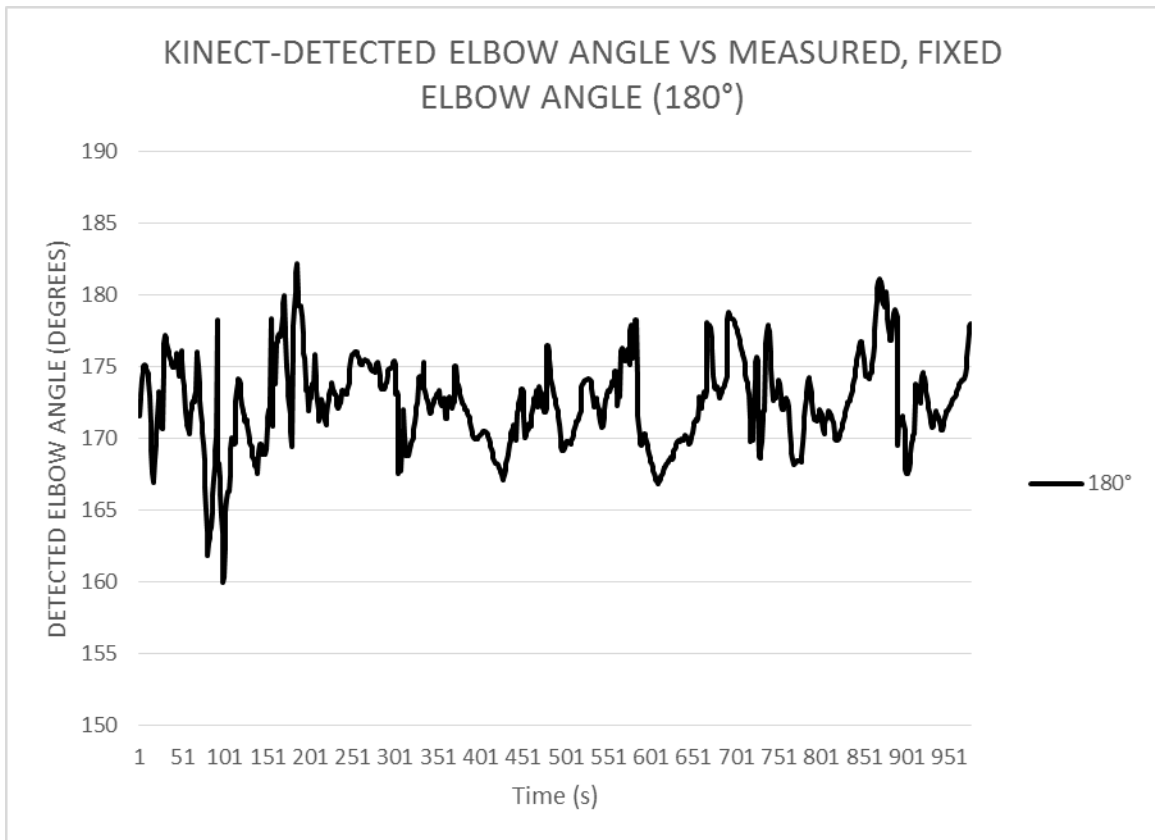
Figure II.2. Plot of Detected Elbow Angle for All Trials, Full Extension (180°)

TEST 2: ELBOW AT PARTIAL FLEXION
KINEMATIC FOCUS: Elbow detection accuracy and precision in partially flexed position
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: With the elbow fixed in partial flexion (135°) using elbow fixation
device, subject moves arm throughout the capture volume for 10 trials while detected elbow angle
is recorded.
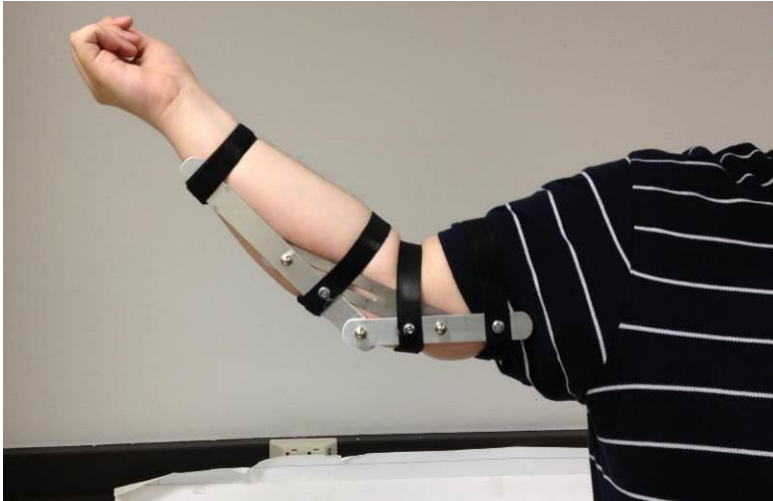
Figure II.3. Testing Configuration

Table II.2. Kinect-Detected Parameters for Exemplar Subject, Elbow at Partial Flexion (135°)

Trial	Detected Value
Trial #1	133.4°±8.3°
Trial #2	136.9°±5.1°
Trial #3	135.9°±1.7°
Trial #4	141.6°±6.6°
Trial #5	135.2°±5.7°
Trial #6	141.4°±4.1°
Trial #7	138.3°±2.2°
Trial #8	137.0°±3.6°
Trial #9	140.7°±2.8°
Trial #10	136.6°±2.0°
Average of All Trials	**137.7°±5.4°**
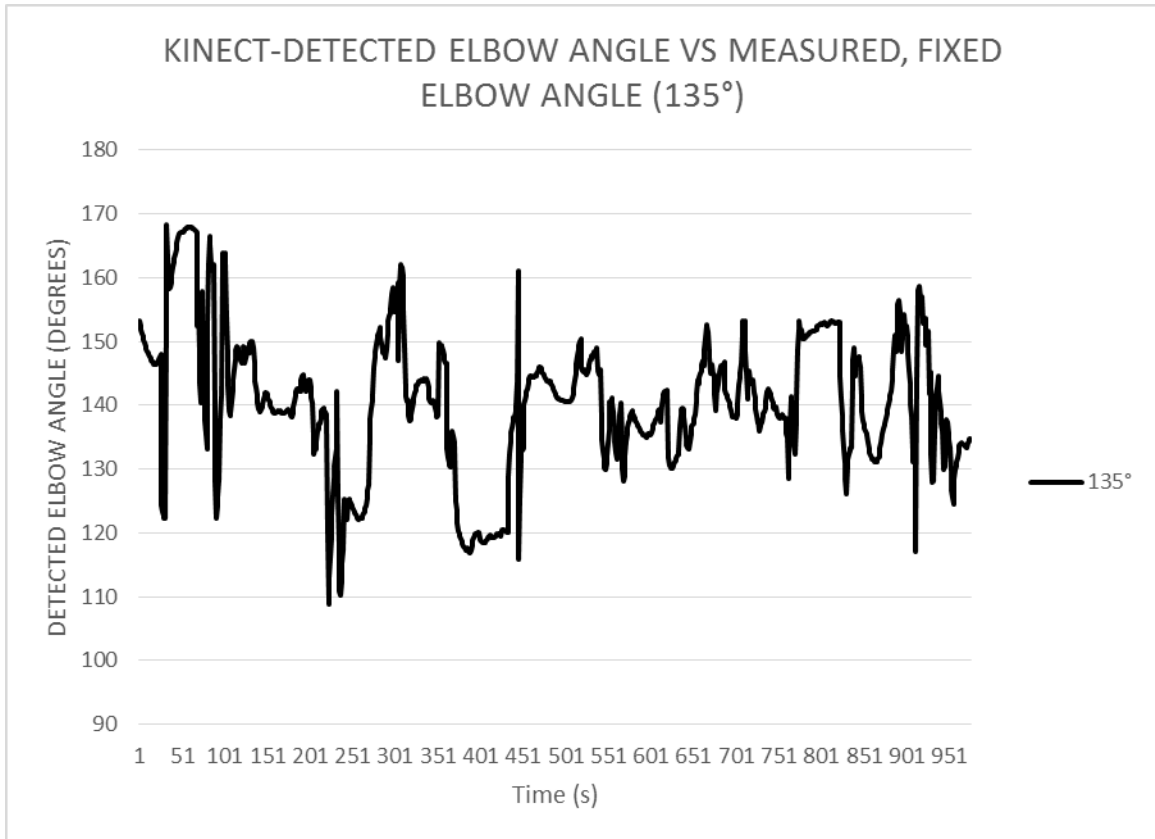
Figure II.4. Plot of Detected Elbow Angle for All Trials, Partial Flexion (135°)

TEST 3: ELBOW FLEXED
KINEMATIC FOCUS: Elbow detection accuracy and precision in flexed position
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: With the elbow fixed in flexion (90°) using elbow fixation device, subject moves arm throughout the capture volume for 10 trials while detected elbow angle is recorded.

Figure II.5. Testing Configuration

Table II.3. Kinect-Detected Parameters for Exemplar Subject, Elbow at Flexion (90°)

Trial	Detected Value
Trial #1	94.9°±4.7°
Trial #2	93.3°±5.4°
Trial #3	93.3°±5.6°
Trial #4	87.3°±2.7°
Trial #5	88.9°±4.5°
Trial #6	98.1°±3.7°
Trial #7	97.7°±5.1°
Trial #8	93.6°±2.5°
Trial #9	95.1°±1.6°
Trial #10	92.6°±4.0°
Average of All Trials	**93.5°±5.3°**
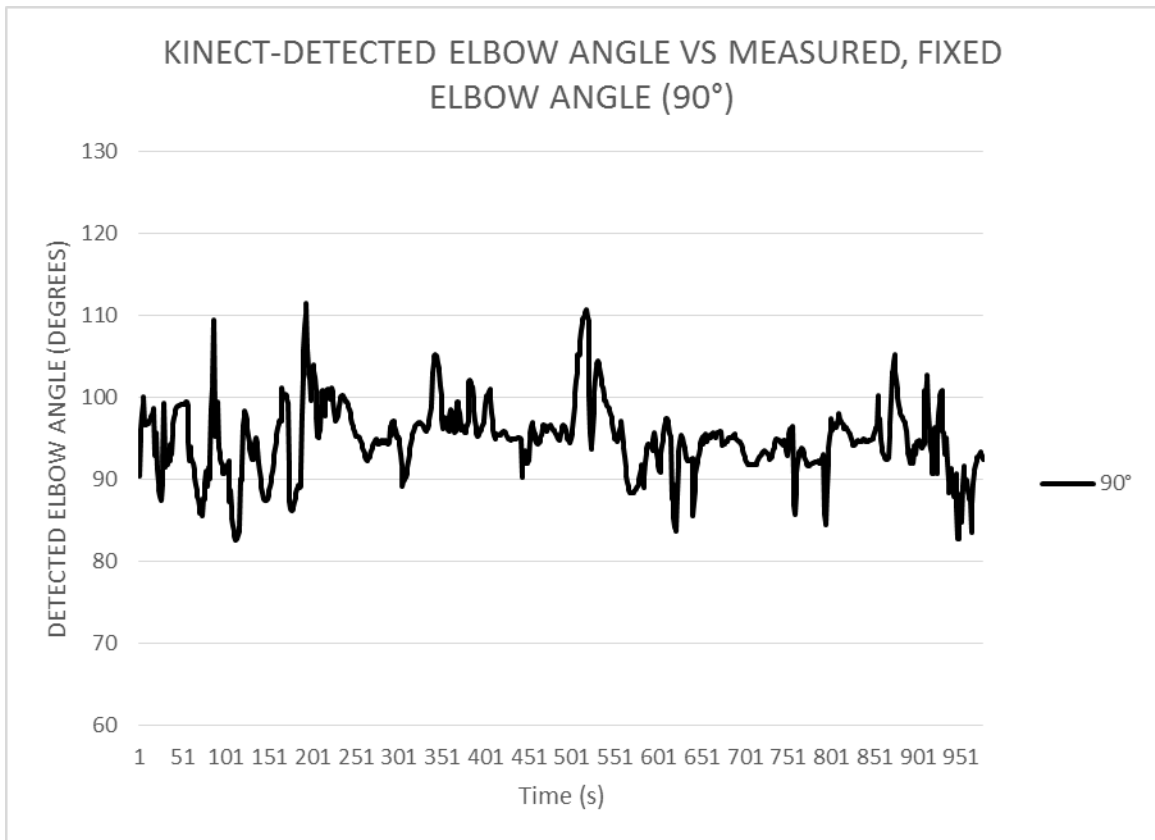
Figure II.6. Plot of Detected Elbow Angle for All Trials, Flexion (90°)

TEST 4: FINGERS AT FULL EXTENSION
KINEMATIC FOCUS: Finger angle detection accuracy and precision in fully extended position
KINECT SYSTEM SETUP: Hand kinematics software – whole-hand mode
TESTING PROTOCOL: With the hand model fixed in full extension (180°), hand model is
moved throughout the capture volume for multiple trials while detected finger angle is recorded.

Figure II.7. Testing Configuration

Table II.4. Kinect-Detected Parameters for Hand Model, Fingers at Full Extension (180°)

Trial	Detected Value
Trial #1	182.8°±9.9°
Trial #2	176.3°±16.9°
Trial #3	176.5°±6.8°
Trial #4	180.5°±10.2°
Trial #5	179.7°±11.4°
Trial #6	178.7°±9.7°
Average of All Trials	**179.1°±11.45°**
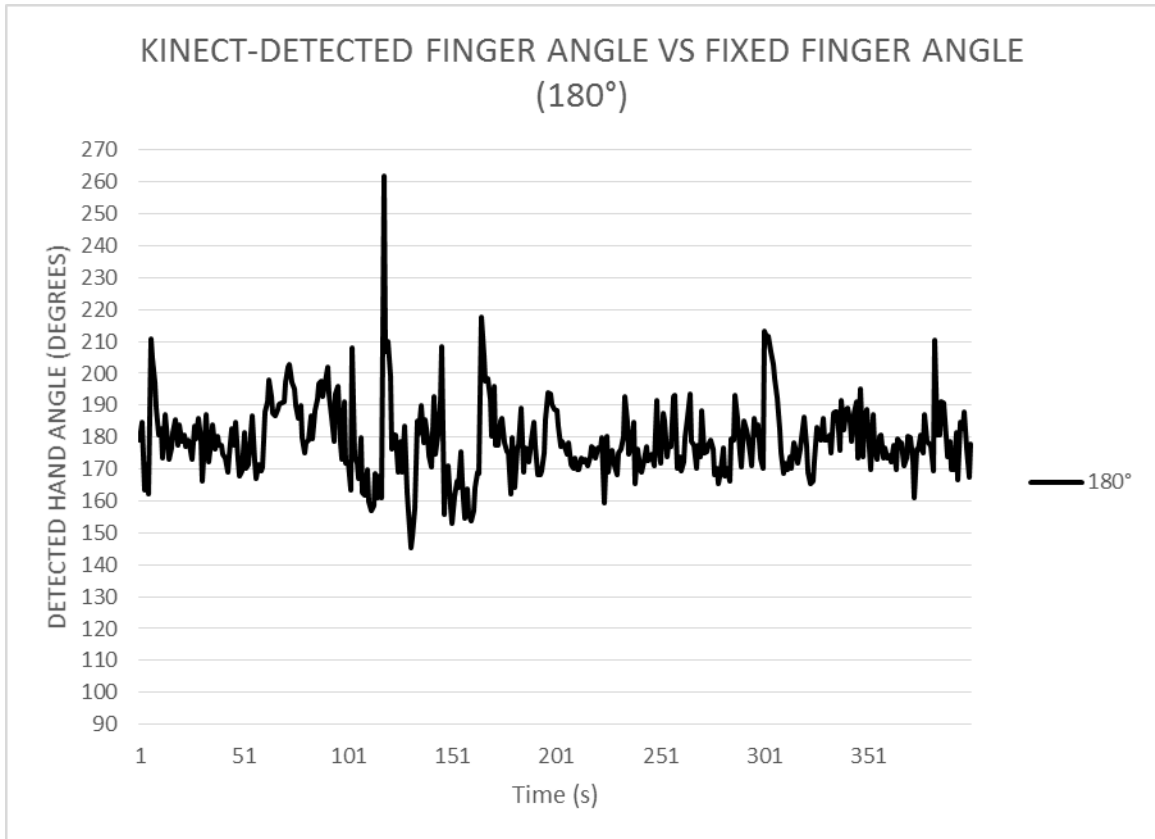
Figure II.8. Plot of Detected Finger Angle for All Trials, Full Extension (180°)

TEST 5: FINGERS AT PARTIAL FLEXION
KINEMATIC FOCUS: Finger angle detection accuracy and precision in partially flexed position
KINECT SYSTEM SETUP: Hand kinematics software – whole-hand mode
TESTING PROTOCOL: With the hand model fixed in partial flexion (45°), hand model is moved throughout the capture volume for multiple trials while detected finger angle is recorded.
NOTE: The data processing software calculates partial flexion at 45° rather than 135°; results are translated 90° for consistency in references to these results in the main text.
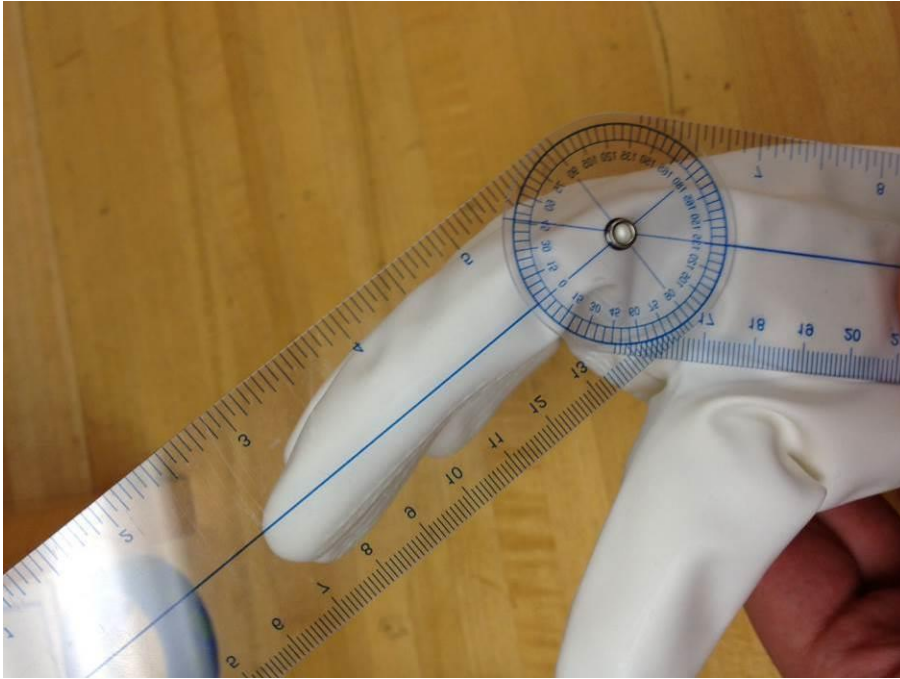
Figure II.9. Testing Configuration

Table II.5. Kinect-Detected Parameters for Hand Model, Fingers at Partial Flexion (45°)

Trial	Detected Value
Trial #1	56.3°±12.8°
Trial #2	42.0°±12.5°
Trial #3	47.4°±11.5°
Trial #4	46.6°±11.4°
Trial #5	54.9°±10.1°
Average of All Trials	**49.4°±12.9°**
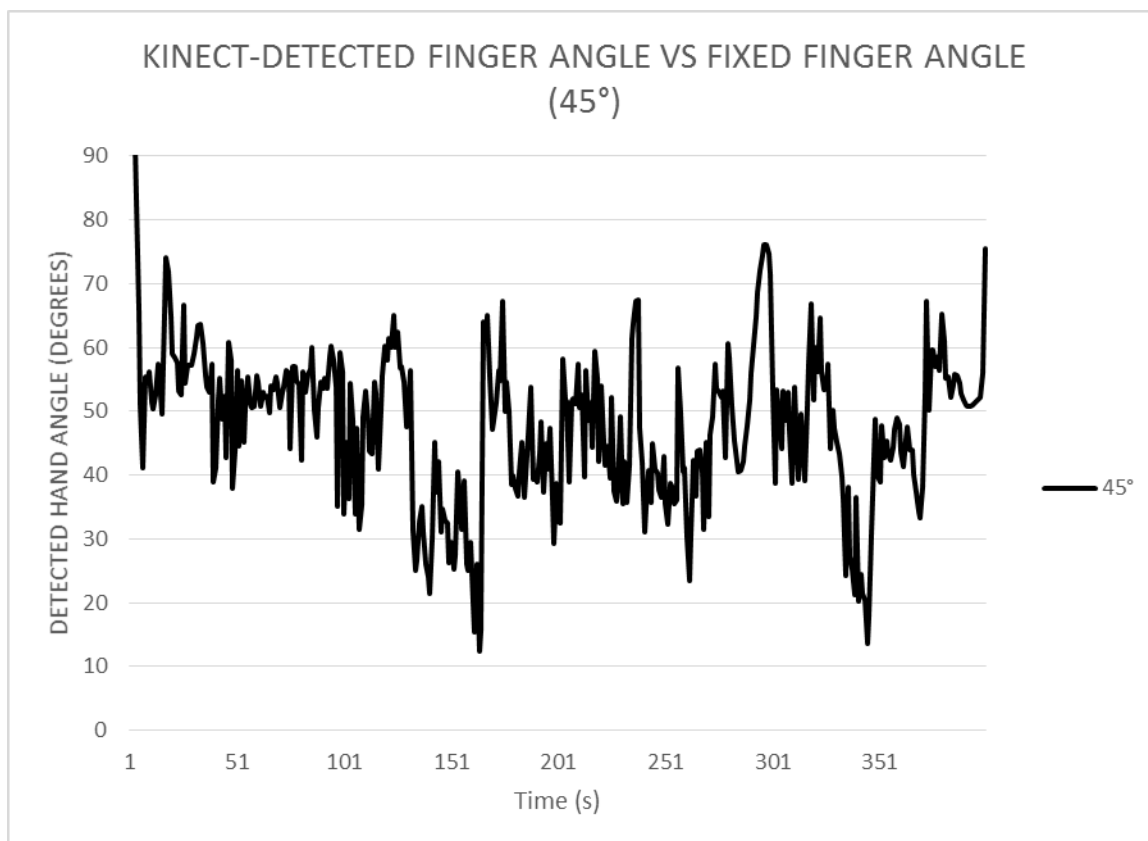
Figure II.10. Plot of Detected Finger Angle for All Trials, Partial Flexion (45°)

TEST 6: FINGERS FLEXED
KINEMATIC FOCUS: Finger angle detection accuracy and precision in flexed position
KINECT SYSTEM SETUP: Hand kinematics software – whole-hand mode
TESTING PROTOCOL: With the hand model fixed in flexion (90°), hand model is moved
throughout the capture volume for multiple trials while detected finger angle is recorded.
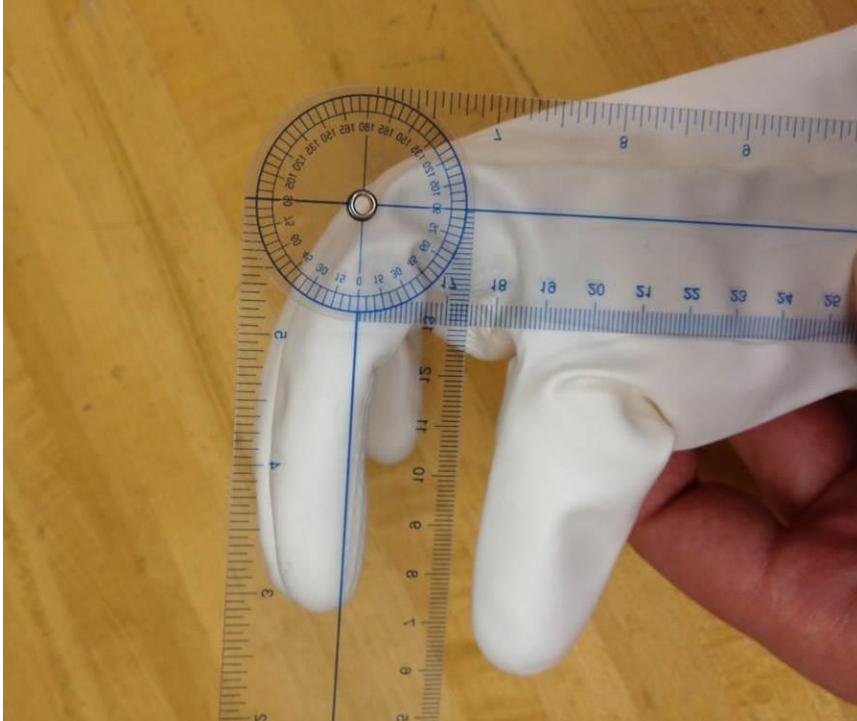
Figure II.11. Testing Configuration

Table II.6. Kinect-Detected Parameters for Hand Model, Fingers in Flexion (90°)

Trial	Detected Value
Trial #1	94.2°±14.6°
Trial #2	106.2°±14.1°
Trial #3	90.0°±21.0°
Trial #4	103.8°±18.1°
Average of All Trials	**98.5°±18.4°**
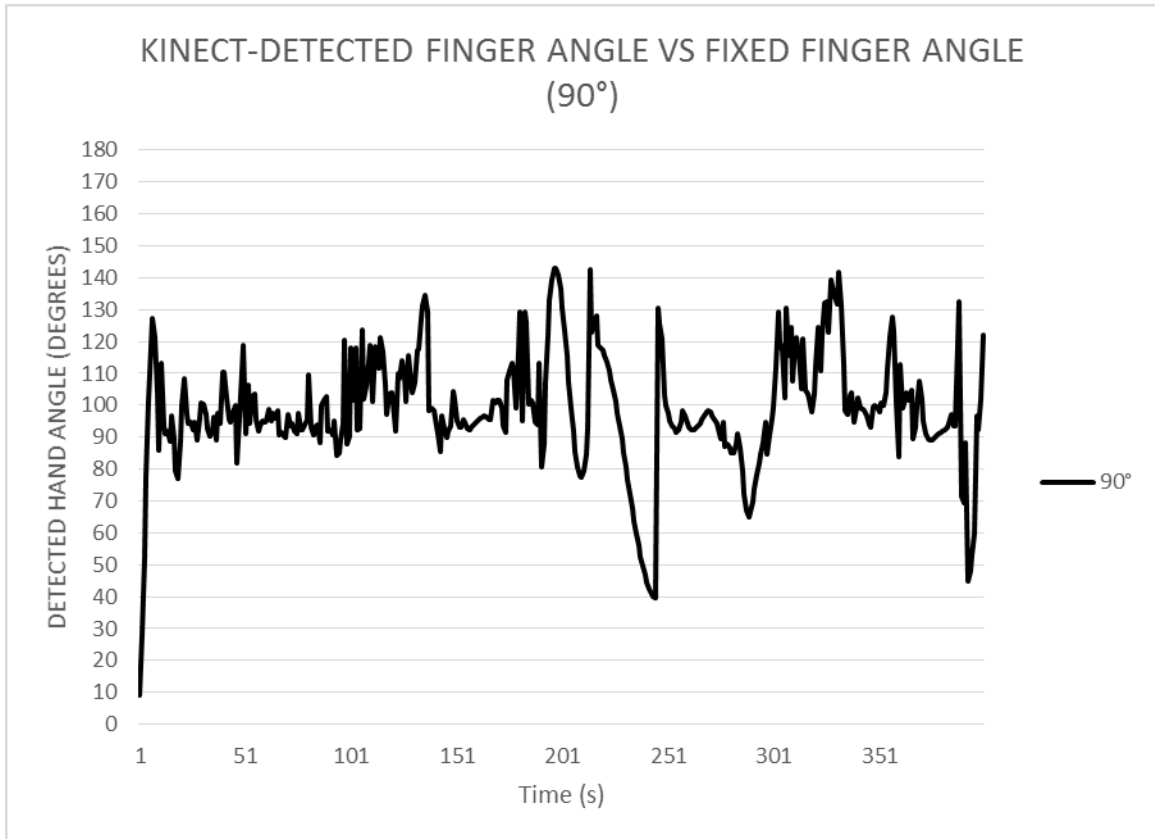
Figure II.12. Plot of Detected Finger Angle for All Trials, Flexion (90°)

APPENDIX III: STUDY PROTOCOL

<table>
<tr><td>Human Research</td><td></td><td>Protocol #:

ORSP #:

Sponsor Tracking #:</td></tr>
</table>

MARQUETTE
UNIVERSITY

Institutional Review Board
Protocol Summary Form

Directions: Submit this completed Protocol Summary Form with original signature(s) along with any additional materials, including consent forms, information sheets, surveys, interview questions, etc.
Submit to: Office of Research Compliance, 560 North 16th Street, Room 102, Milwaukee, WI 53233
Phone: 414-288-7570   **Fax:** 414-288-6281   **Web site:** http://www.mu.edu/researchcompliance

Type of Review being sought: Exempt ☐   Expedited ☒   Full Review ☐

Exempt Review: Submit **originals** of all materials; 1 copy of grant application.
Expedited Review: Submit **originals** <u>AND **1 copy**</u> of all materials; 1 copy of grant application.
Full Review: Submit **originals** <u>AND **14 copies**</u> of all materials; 1 copy of grant application.

Principal Investigator: *Jacob R. Rammer*
Department: *Biomedical Engineering*
Phone: *414-288-8211 (lab)*
E-mail: *jacob.rammer@marquette.edu*

Project Title: *Partial Automation and Quantitative Enhancement of the "Shriners Hospital for Children Upper Extremity Evaluation" using Microsoft Kinect*

PI Certification
By signing below or submitting this document electronically, I agree to accept primary responsibility for the scientific and ethical conduct of this project as approved by the IRB. The project cannot begin until I receive documentation of IRB final approval.

	Jacob R. Rammer	
Signature of Principal Investigator	Printed Name	Date

FOR STUDENTS, a Marquette faculty supervisor's signature is required or this document must be submitted electronically by the supervisor. **Faculty Supervisor:** By signing below or by submitting this document electronically, I certify that I have reviewed the research plan and this document and I have approved the scientific and ethical aspects of the project. I will supervise the above listed student and ensure compliance with human subjects' guidelines.

	Dr. Gerald F. Harris	Biomedical Engineering
Signature of Faculty Supervisor	Printed Name	Department

For Office Use Only

Human Subjects Committee

Disposition: Exempt   Expedited   Full Review   Approved through ____/____/____

_____   ____/____/____
Signature of Institutional Review Board Representative   Date

_____   ____/____/____
Signature of Institutional Review Board Chair   Date

1

Please note that in order to choose any of the check boxes on this form, you must double click the box and select "Checked" as the Default Value

Section A: RESEARCH PROJECT CHARACTERISTICS

1. This is a:
☐ Research Proposal
☒ Thesis/Dissertation
☐ Class Project (list Dept. & Course #):
☐ Other (specify):

2. Grant or Contract Funded: ☐ Yes ☐ Funding is Pending ☒ No

Sponsor/Source of funding:

If external funding, have you registered your project with Research and Sponsored Programs (ORSP)?
☐ Yes ☐ No
If Yes, Please list your ORSP Reference #:_____

If your project is grant funded, submit a copy of the funding/grant proposal and list the AGENCY GRANT NUMBER:_____

If the project title listed on page 1 of this application is different from your grant title, list the grant title:_____

If the funding agency requires an official IRB approval letter or form, list the program area, contact person, title and complete mailing address:

3. Does the investigator or key personnel have a potential financial conflict of interest in this study that should be disclosed?
☐ Yes ☒ No If Yes, Please explain:

4. PI Status:
☐ Undergraduate
☒ Graduate
☐ Faculty/Administrator
☐ Other (specify):

5. Provide the names, titles and affiliations of **all** investigators (include yourself, co-PIs, other investigators, and students). Please use an attachment if more space is required.

OHRP interprets an "**investigator**" to be any individual who is involved in conducting human subjects research studies. Such involvement includes:
- obtaining information about living individuals by intervening or interacting with them for research purposes;
- obtaining identifiable private information about living individuals for research purposes;
- obtaining the voluntary informed consent of individuals to be subjects in research; and

Please submit completed **original plus required copies** to Marquette University's Office of Research Compliance, 560 N. 16th Street, Room 102, Phone: 414-288-7570, Fax: 414-288-6281.

- studying, interpreting, or analyzing identifiable private information or data for research purposes.

Note that any collaborative work with another institution will require the submission of that institution's IRB approval letter.

Name	Institution	Status (Faculty, Grad., Undergrad., etc.)	Project Role (Co-PI, Key or Non-Key Personnel, Consultant, etc.)	Contact e-mail	Tutorial* (Attached or On File w/ MU ORC)
Jacob R. Rammer	Marquette University	Graduate Student	PI	Jacob.rammer@marquette.edu	On File
Gerald F. Harris	Marquette University	Faculty	Investigator	Gerald.harris@marquette.edu	On File
Susan Riedel	Marquette University	Faculty	Investigator	Susan.riedel@marquette.edu	On File
Joe Krzak	Shriners Hospitals for Children--Chicago	Staff	Key Personnel	jkrzak@shrinenet.org	On File at SHC

*Please note that Training Certificates are required for all human subject investigators. Certificates can be obtained by visiting <u>http://phrp.nihtraining.com/users/login.php</u> and completing the IRB Tutorial Designed by the National Institute of Health. <u>Copies</u> of Training Certificates are to be forwarded to the Office of Research Compliance.

6. Do you wish to have this project considered for Exempted Review?
☐ Yes ☒ No (See Submission Requirements on ORC web site for definition and list of categories)

If Yes, identify the Exemption category number you believe covers your project:
☐ Category 1 ☐ Category 2 ☐ Category 3 ☐ Category 4 ☐ Category 5
☐ Category 6

Explain your basis for this level of review here:

7. Do you wish to have this project considered for Expedited Review?
☒ Yes ☐ No (See Submission Requirements on ORC web site for definition and list of categories)

If Yes, identify the Expedited Review category number you believe covers your project:
☐ Category 1 ☐ Category 2 ☐ Category 3 ☒ Category 4 ☐ Category 5
☒ Category 6 ☐ Category 7

Explain your basis for this level of review here:
Data collection involves multiple components: Video recordings will be taken of subjects performing activities to be analyzed/scored from video recordings later, using a standardized validated system in current clinical use (category 6), and skeletal position data will be obtained through the Microsoft

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Kinect sensor, which is a markerless data collection system that does not contact the subject, while the subject performs activities of daily living (category 4). Level of risk is minimal and consistent with activities of daily living, as data collection methods are entirely non-invasive and do not contact the subject.

8. Inclusive dates of Project: (Project may not start prior to approval)

From*: IRB Approval Date*   To*: January 1, 2014*

9. How long is the active involvement of participants in the study? (e.g. six half-hour sessions over six months)*: One session per subject, 1-Hour expected maximum*

10. Research Location: Where will the research be performed (if not on campus, please provide the full address; if online, please indicate online)*? Marquette University, Olin Engineering, Room 323*

Note: If the research will be conducted in a school or institution other than Marquette University, include a letter, on letterhead stationery, of permission from that institution and/or its IRB. This letter must be received by the ORC prior to IRB approval.

11. What do you intend to do with the data collected?

☒ Publish paper   ☒ Present at conferences/meetings
☒ Other (please describe)*: Master's Thesis*

Section B: SUBJECT RECRUITMENT

12. Indicate which of the following specially protected groups will be specifically targeted as research participants in this study (Check all that apply):

☐ Pregnant Women/Fetuses   ☒ Children (minors under 18)   ☐ Prisoners
☐ None of These

13. Indicate which of the following potentially vulnerable populations will be specifically targeted as research participants in this study (Check all that apply):

☐ College Students*   ☐ Institutional Residents   ☐ Cognitively Impaired
☐ Physically Disabled   ☐ Terminally Ill   ☒ None of These

*If using Marquette students, please consult HRP Policy 98.102 Participation of Students and Employees in Research (http://www.marquette.edu/researchcompliance/human/documents/HRPolicy98.102-StudentsEmployees.pdf)

14. Will both genders have an equal opportunity to participate as subjects in this research project?
☒ Yes   ☐ No   If No, explain your answer*:*

15. Will subjects of different racial and ethnic consideration have an equal opportunity to participate in this research project? ☒ Yes   ☐ No   If No, explain your answer*:*

Please submit completed **original plus required copies** to Marquette University's Office of Research Compliance, 560 N. 16th Street, Room 102, Phone: 414-288-7570, Fax: 414-288-6281.

16. How many subjects will be recruited into your research project as justified by the hypothesis and study procedures?

a) Total number of subjects required to complete your study*: 16*

How was this number determined? If a power analysis or other method was used, please include this in your response: *Past study (Davids et al, 2006) used 11 subjects for reliability study and 20 for concurrent validity study, this is the average of similar studies.*

b) Total number of subjects to be recruited (to account for drop out, etc.)*: 20*

c) Explain the reason for difference between (a) and (b) above (e.g. past studies have shown that there is a 50% drop out rate for students, the study is longitudinal and a drop out rate of 30% is anticipated)*: Past Studies indicate 25% dropout rate.*

Please Note: If at a later time it becomes apparent that you need to increase your sample size, you will need to submit an IRB Protocol Amendment Form, including your justification for additional subjects.

17. What is the age range of subjects (please provide a specific range)*? 12YR-17YR*

18. What is the source of the subject list*? Fliers posted and handed out during Marquette Summer Engineering Academies for high-school students & Announcement through News Briefs (Friends and family of students, faculty, and staff)*

19. Who will contact the subjects (name and affiliation)*? Jacob Rammer, Graduate Student, Marquette University, Biomedical Engineering*

20. How will subjects be contacted? (Check all that apply)

☒ Advertisements*   ☐ Letters*   ☐ Notices*
☐ Telephone Lists   ☐ Student Pool   ☐ Random Telephone Dialing
☒ Direct person-to-person solicitation   ☐ E-mail*
☒ Other (please specify): *Flyers will be distributed directly at*   ☒ University News Briefs*
    Marquette Engineering Summer Academies and posted
* A copy must be submitted for IRB approval. For letters, notices, advertisements, and others, submit verbatim copies.

21. Data collection methods: (Check all that apply and **provide copies of all tools**)

☐ Questionnaire or Survey[1]   ☐ Observation[4]   ☐ Interview
☐ Archival Data[2]   ☐ Intervention   ☒ Video Recording[3]
☐ Instruction/Curriculum   ☐ Focus Groups   ☐ Audio Recording[3]
☒ Testing/Evaluation   ☐ Other (please describe):

[1] If conducting an online survey, consult the University's Online Survey Policy
    (http://www.mu.edu/upp/documents/upp1-22.pdf)
[2] If using archival data, describe in the Narrative section (question 48) whether data are de-identified.

Please submit completed **original plus required copies** to Marquette University's Office of Research Compliance, 560 N. 16th Street, Room 102, Phone: 414-288-7570, Fax: 414-288-6281.

[3] If you select video and/or audio recording, please provide further explanation in the Narrative section (question 48) regarding confidentiality of the recording(s).

[4] If you select observation, please provide further explanation in the Narrative section (question 48) regarding who you plan to observe, where you plan to observe (public or private location), and the type of data you will be collecting.

NOTE: If data collection tools are provided in a language other than English, provide both the English and non-English versions.

22. If deception or experimental manipulation is used, please explain why it is necessary (as opposed to convenient) for this study. Include plans for how and when subjects will be debriefed and attach a copy of your debriefing sheet, if applicable: *n/a*

23. Does any part of this activity have the potential for coercion of the subject (for example, a student being recruited by a teacher who controls his or her grade may feel coerced)? ☐ Yes ☒ No

24. If Yes, explain and describe the proposed safeguards: *n/a*

Note: If you are planning to recruit Marquette employees or students, consult the HRP Policy regarding Participation of Students and Employees in Research (http://www.marquette.edu/researchcompliance/human/documents/HRPolicy98.102-StudentsEmployees.pdf)

Section C: CONSENT OF RESEARCH SUBJECT

25. What type of consent will be used? **You must attach a clean copy that will receive the IRB approval stamp. Consult the ORC website for the consent form instructions and required template.**

☐ Written Consent   ☐ Waiver   ☐ Online Consent
☐ Oral Consent   ☐ Information Sheet   ☒ Parent Permission & Child Assent
☐ Guardian Permission & Adult Assent   ☐ Other (please describe):

26. If you are requesting a waiver of informed consent, address each of the following:
a) The research involves no more than minimal risk to the subjects;
b) The waiver will not adversely affect the rights and welfare of the subjects;
c) The research could not practicably be carried out without the waiver; and
d) Whenever appropriate, subjects will be provided with additional pertinent information after participation.

Considering the above requirements for a waiver of informed consent, please describe how your research qualifies for this waiver: *n/a*

27. Do you intend to use an informed consent document in a language other than English?
☐ Yes ☒ No   If Yes, provide both the English and non-English versions.

Please submit completed **original plus required copies** to Marquette University's Office of Research Compliance, 560 N. 16th Street, Room 102, Phone: 414-288-7570, Fax: 414-288-6281.

28. If you are using an oral consent, describe the rationale, how it will be documented, and include a copy of the oral presentation; it must include all information required of written informed consents: *n/a*

Section D: CONFIDENTIALITY

29. Where specifically will consent forms be kept (building location, room #, please include full address if off campus) **AND** who will have access*? Consent forms will be kept in a locked file cabinet in Olin Engineering, 323 AND/OR ASF 105 and will only be accessible to study personnel.*

30. How will research subjects be identified in the research data (by name, code, number, etc.)*? Data will be referenced by randomly assigned identification number.*

31. At any time during your research will a direct link exist between collected data and research subjects? (i.e. participants' data can be directly linked to their name). For example, data collection sheet has a location for participant's name to be recorded.
☐ Yes ☒ No

At any time during your research will an indirect link exist between collected data and research subjects? (i.e. participants' data can be indirectly linked to their name.) For example, data collection sheet has a location for subject number to be recorded. In addition, a spreadsheet exists that links that subject number to a participant's name. Many multi-session and longitudinal studies use indirect links.
☒ Yes ☐ No

If either of the two above questions are answered "yes," please describe the provisions for security of any links*: Database linking names to research IDs will be stored in a locked file cabinet in Olin Engineering, 323 AND/OR ASF 105. Video recordings will not contain the subject's name but may contain the subject's face and could therefore be identifiable. Video recordings will be used to score subject's performance on the SHUEE. Recordings will be stored on a secured, password-protected computer.*

32. When data results are reported/disseminated:
Will identifiers be used (for example: participant's name will be published in article)? ☐ Yes ☒ No

Will it be presented in aggregate form (For example: Group characteristics only=Yes, Individual Quotations=No)?
☒ Yes ☐ No

33. Will research data (raw data) be available to anyone other than the IRB, sponsor and study personnel?
☐ Yes ☒ No

If Yes, who will this data be shared with, describe how the data will be safeguarded, and be sure to include this information in the consent form (if applicable):

Please submit completed **original plus required copies** to Marquette University's Office of Research Compliance, 560 N. 16th Street, Room 102, Phone: 414-288-7570, Fax: 414-288-6281.

34. Describe how research records, data, electronic data, **(including deidentified data)** etc. will be stored (i.e. locked file cabinet, password protected computer file, etc.) **AND** for how long (research records must be maintained a minimum of 3 years; if kept indefinitely, please state this and indicate it on the consent form)*: Hard copies of data and video recordings will be stored in locked file cabinets in Olin Engineering, 323 AND/OR ASF 105. All digital data will be stored on password-protected computers and drives. Data will be stored for 10 years following study completion.*

35. Describe how the research records, data, electronic data, **(including deidentified data)** etc. will be destroyed (i.e. shred paper documents, delete electronic files, etc.), **AND** address whether they may be used for future research purposes (If records will be used in the future, please indicate this on the consent form)*: After 10 years following study completion, hard copies of data and video recordings will be destroyed and digital data permanently deleted. Video recordings will be stored digitally (compressed digital video file) on a secured, password-protected computer and will be destroyed by secure deletion of files.*

36. Could any part of this activity result in the potential identification of child/adult/older adult abuse?
☐ Yes   ☒ No

If Yes, is the mandatory report of child/adult abuse outlined in your consent?
☐ Yes   ☐ No

37. Could any part of this activity result in the potential identification of communicable diseases or criminal activities? ☐ Yes   ☒ No

Section E: BENEFITS AND RISKS TO RESEARCH SUBJECTS

38. Are the direct and indirect benefits to the research subjects for involvement in this project described in their informed consent form? ☒ Yes   ☐ No

39. Describe the possible direct benefits to the subjects. If there are no direct benefits, please state this. Also, describe the possible benefits to society*: Benefits to subjects: Since subjects will be primarily recruited from Marquette Engineering summer pre-college programs, participation in a research study might serve to supplement the learning experience and spark interest in biomechanics research for these future engineers. Benefits to society: This study will validate a system for low-cost, easy-to-use, kinematic analysis for the upper extremity which will increase clinical effectiveness and patient enjoyment for analysis of conditions such as cerebral palsy.*

40. Will any electrical or mechanical systems that require direct human contact be used (does not include use of computers for data keeping and surveys)? ☐ Yes   ☒ No *Neither the SHUEE nor the Kinect system involve any devices, sensors, or electrical equipment to be in contact with the subject. Subjects perform typical activities of daily living, sometimes using typical objects like utensils or toys, while being recorded via video or non-contact depth sensor (Kinect).*

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If Yes, attach a copy of the manufacturer's electrical/mechanical <u>safety</u> specification information for each instrument/device. If the device is custom made, attach detailed description/information on design and safety with respect to human subjects application.
***Also include the most recent safety inspection information documented on either the <u>Marquette University Electrical Safety Testing Documentation</u> form or an equivalent electrical safety testing documentation form.

NOTE: Electrical and mechanical safety inspections must be performed and documented on an annual basis. Documentation of the most recent safety inspection must be submitted with the initial protocol, as well as with any subsequent 3-year renewals.

41. Are the nature and degree of potential risks to research subjects described in the consent? Risks can be physical, psychological, economic, social, legal, etc.
☒ Yes ☐ No

42. Describe the risks to participants and the precautions that will be taken to minimize those risks (these risks should also appear on the consent form). If no risks identified, explain why*: Subjects will perform tests consistent with typical activities of daily living, and will have no contact with electrical or mechanical lab instrumentation. There will, however, be contact with typical objects meant to simulate certain activities of daily living. These include Play-Doh (commercially available from Hasbro, Inc – non-toxic, conforms to ASTM D-4236), standard kitchen utensils (fork and butter knife), wooden beads, plastic bottle with lid, cotton string, paper money and coins, stickers, and ping-pong balls. These objects present minimal risk, but should any allergic reaction or any other issue occur, the subject will be able to withdraw from the project at any time. An additional risk could be the loss of confidentiality of subject information, which will be minimized through strict security of hard-copy information, video recordings, and digital data.*

Section F: COMPENSATION FOR RESEARCH SUBJECTS

43. Will research subjects be compensated or rewarded? ☒ Yes* ☐ No

If Yes, describe the amount of compensation, how and when it will be disbursed, and in what form*: Compensation of $25.00 will be paid through Marquette University following testing. W-9 and fee agreement forms will be completed at time of testing. Forms will be processed and a check will be cut and mailed to the address listed on the forms. Should the subject withdraw after beginning testing, compensation will still be provided.*

* If subjects are recruited from MU classes, indicate whether students are receiving course credit (regular or extra credit) and, if so, what alternatives are offered to those students who do not wish to participate in the research.

Section G: NARRATIVE DESCRIPTION
For the following questions, try to use **non-technical** language that provides a first time reader (from any discipline) with a clear understanding of the research, and avoid abbreviations. **Do not "paste" text from the grant proposal, and do not refer to the grant proposal page numbers or include**

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literature citations. Information given should provide the first-time reader with a clear understanding of the proposed research. Focus your answers on the involvement and treatment of human subjects.

PROPOSED RESEARCH RATIONALE

44. Describe why you are conducting the study and identify the research question(s) being asked*: A new system that uses the Microsoft Kinect video game sensor to track skeletal motion of the hand and arm has been developed. This system will be used to augment the "Shriners Hospital Upper Extremity Evaluation (SHUEE)," to assess upper extremity function in children with cerebral palsy. The subject is video recorded while performing various activities of daily living, and is scored later by therapists to indicate level of upper extremity capability. The purpose of this study is to test this new Kinect system on normal subjects alongside the SHUEE, using similar standardized activities, evaluating the Kinect system by direct comparison of scored results from both evaluations. Thus, the primary question being asked is whether the Kinect system has the potential to be clinically effective in this role as a clinical motion analysis platform, as a precursor to future studies involving children with cerebral palsy and other upper extremity disorders.*

SUBJECTS TO BE INCLUDED

45. Describe any inclusion and/or exclusion criteria*: Normal subjects will be recruited for this study. Subjects must have no injuries or impairments of arm or hand movement. Subjects will ideally be 12-17 years old, with 50% male/50% female. Subjects will be required to wear short sleeves for testing, and remove any reflective jewelry or watches to avoid interference with motion sensor.*

RECRUITMENT AND OBTAINING INFORMED CONSENT

46. Describe your recruitment process in a step-by-step manner*: Flyers will be distributed on campus bulletin boards and during Marquette Engineering summer academies and an approved university news brief announcement submitted containing relevant information regarding the purpose of the study, eligibility criteria, compensation, and contact information. Interested subjects will respond to the PI by email. Those subjects who are confirmed to be eligible to participate and fit recruitment criteria will be placed in the study. An appointment will be set up for the subject and a parent or legal guardian at Olin Engineering 323.*

47. Describe your informed consent process in a step-by-step manner: *Upon arrival to the lab, the subject and their parent/guardian will be provided with an informed consent form (attached), and investigators will ensure the subject and parent/guardian's understanding of the form, with as much time as needed allotted for this process. Testing will begin following the consent process and the subject will be able to withdraw at any point in the study.*

SPECIFIC PROCEDURES TO BE FOLLOWED

48. Describe the methodology to be used and describe in a step-by-step manner the involvement and treatment of human participants in the research, through to the very end of participation. Identify all data to be collected*: This study is designed to compare two methods for evaluation of upper*

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extremity motion, the Shriners Hospital for Children Upper Extremity Evaluation (SHUEE), a widely-used clinical methodology for evaluating children with cerebral palsy, and the newly developed Kinect system. The SHUEE is a therapist-led evaluation, where the subject is asked to perform certain activities of daily living, sometimes using utensils, toys, or other implements, while being video recorded; this recording is then scored later by therapists to indicate upper-extremity performance. The Kinect system is designed to be similar to the SHUEE, where the subject performs similar activities of daily living but is recorded by the Kinect video game sensor, which calculates skeletal position using a non-contact depth sensor. These systems allow therapists to determine quality and quantity of arm motion.

20 subjects between the ages of 12-17, with no upper-extremity impairments – 50% male, 50% female – will be recruited to participate in this study through flyers distributed through Marquette Engineering summer events for high-school students and Marquette News Briefs directed toward friends and family members of faculty, staff, and students. Subjects who express interest and conform to study recruitment parameters will be explained the entire testing procedure, given and explained fully an informed consent form, and informed that they may choose to withdraw at any time. Once consent has been obtained, the subject will use the Kinect system in simple games or activities meant to familiarize the subject with the skeletal tracking functions. Then, testing will begin. The first phase of testing is the performance of the Shriners Hospital Upper Extremity Evaluation (SHUEE), a standardized and validated testing methodology in current clinical use at Shriners Hospitals for Children. Subjects perform simple activities of daily living at the direction of a therapist while being video recorded; subjects have no contact with sensors or electronic devices. This testing is video recorded for later analysis of upper extremity function, and the following activities will be performed by the subject:

- *Removing paper money from wallet*
- *Folding pieces of computer paper*
- *Tearing pieces of computer paper*
- *Stringing large wooden beads onto cord*
- *Unscrewing a wide-lid bottle cap*
- *Pulling apart Play-Doh cylinders*
- *Cutting Play-Doh with butter knife*
- *Throwing large ball*
- *Accept change (coins) into hand*
- *Receive low "5" (from test personnel)*
- *Take object to mouth from table*
- *Touch opposite ear with hand*
- *Place a sticker on a large ball*
- *Put on socks*
- *Fasten shoes*
- *Crawl*
- *Demonstrate hand grasping/releasing of wooden bead*

Regarding the video recordings taken as part of the SHUEE analysis, recordings will be used to score upper extremity performance, and once scores are obtained, the recordings will no longer be needed and will remain confidential and stored in a locked filing cabinet. This is consistent with the clinical methodology employed at Shriners Hospitals for Children when implementing this evaluation.

Next, the Kinect-based portion of the testing will begin. The subject will be seated in front of the Kinect sensor, which will record skeletal position information throughout testing for later

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analysis. This is similar to the SHUEE testing, in that the subject is directed to perform activities while being recorded via the Kinect sensor, which is non-contact and senses the position of the subject's skeleton by a depth sensor. The following activities will be performed by the subject for multiple iterations in a repetitive pattern:

- *Grasp/Release of hand*
- *Thumb/Index-Finger Pinch*
- *Wrist range-of-motion flexion/extension activity*
- *Elbow range-of-motion flexion/extension activity*
- *Shoulder range-of-motion abduction/adduction activity*
- *Unscrewing a wide-lid bottle cap*
- *Pulling apart Play-Doh cylinders*
- *Cutting Play-Doh with butter knife*
- *Throwing ping-pong balls*
- *Place sticker on a large ball*
- *Put on socks*
- *Fasten shoe*

This will mark the completion of testing and subjects will be thanked for their participation.

Please submit completed **original plus required copies** to Marquette University's Office of Research Compliance, 560 N. 16th Street, Room 102, Phone: 414-288-7570, Fax: 414-288-6281.

12

Research Study

for

Normal Healthy Teens

to Measure Arm and Hand Motion using Microsoft Kinect

Conducted By: **Jacob R. Rammer**
Orthopaedic & Rehabilitation Engineering Center(OREC)
Marquette University

Sponsored by: **Orthopaedic & Rehabilitation Engineering Center (OREC)**
Marquette University

Study Location: **OREC/Marquette University**
Olin Engineering, Room 323
Marquette University

Purpose:
The purpose of this research study is to test a newly developed system that uses the Microsoft Kinect video game motion sensor to measure arm and hand motion while you are performing simple activities designed to be similar to daily living activities. The primary goal of this study is to determine if the Kinect evaluation is effective for normal individuals so that it may be applied to children with cerebral palsy and other clinical applications in the future.

Procedure:
Participation will involve a single 1-hour lab visit, where participants will perform various activities meant to approximate activities of daily living, such as throwing a ball, grasping objects, and tying shoes.

Eligibility:
- Must be between the ages of 12-17
- No injuries or impairments of arm or hand motion

Benefits/Compensation:
- First-hand exposure to biomechanics research!
- You will receive $25.00 for your time and involvement in this study.

For more information, please contact Jacob Rammer, Graduate Student in Biomedical Engineering (jacob.rammer@marquette.edu)

| **Arm and Hand Kinect Study**

For more information contact:
Jacob Rammer, Graduate Student in Biomedical Engineering
jacob.rammer@marquette.edu | **Arm and Hand Kinect Study**

For more information contact:
Jacob Rammer, Graduate Student in Biomedical Engineering
jacob.rammer@marquette.edu | **Arm and Hand Kinect Study**

For more information contact:
Jacob Rammer, Graduate Student in Biomedical Engineering
jacob.rammer@marquette.edu |

UNIVERSITY NEWS BRIEF:

Participants sought for Arm & Hand Kinect Study

Volunteers for the research study "Partial Automation and Quantitative Enhancement of the Shriners Hospital for Children Upper Extremity Evaluation using Microsoft Kinect" are needed to determine the effectiveness of the system in normal subjects.

Participants will be asked to perform activities of daily life, including folding and tearing paper, stringing wooden beads onto a cord, unscrewing a bottle cap, pulling apart and cutting Play-Doh, throwing a ball, moving objects and hand gestures, placing a sticker on a ball, putting on socks, fastening shoes, and crawling while motion is recorded using a video camera and the Microsoft Kinect video game sensor. Participants must:

- Be between the ages of 12-17
- Have no injury or impairment of arm or hand function
- Attend a single 1-hour visit to the Orthopaedic & Rehabilitation Engineering Center lab in Olin Engineering

Participants will be compensated $25.00 for their time and gain firsthand exposure to biomechanics research taking place at Marquette.

For more information contact Jacob Rammer, Graduate Student in Biomedical Engineering, via email at jacob.rammer@marquette.edu

This study is being conducted by Dr. Gerald F. Harris, Professor of Biomedical Engineering, and Jacob Rammer.

The study has been approved by Marquette's Institutional Review Board for the protection of human subjects. For more information about research participant rights, contact the Office of Research Compliance, 8-7570.

Protocol Number: HR-2638

MARQUETTE UNIVERSITY
AGREEMENT OF CONSENT/ASSENT FOR RESEARCH PARTICIPANTS
Partial Automation and Quantitative Enhancement of the "Shriners Hospital for Children Upper
Extremity Evaluation" using Microsoft Kinect
Jacob R. Rammer
Biomedical Engineering

You have been invited to participate in this research study. Before you agree to participate, it is important that you read and understand the following information. Participation is completely voluntary. Please ask questions about anything you do not understand before deciding whether or not to participate.

PURPOSE: The purpose of this research study is to test a new system that uses the Microsoft Kinect video game motion sensor to measure arm and hand motion and skeleton position while you are performing simple activities. The goal is to determine if this system is effective by testing normal individuals with both the new Kinect evaluation and the clinical "Shriners Hospital Upper Extremity Evaluation" to determine if the Kinect system is effective. If so, the system may be applied to test children with upper extremity clinical needs. You will be one of about 20 participants in this study.

PROCEDURES: First, you will perform the Shriners Hospital for Children Upper Extremity Evaluation, which uses simple activities meant to be similar to activities of daily living, such as removing paper money from a wallet, folding and tearing paper, stringing wooden beads onto a cord, unscrewing a bottle cap, pulling apart and cutting Play-Doh, throwing a ball, accepting coins and low "5" from test personnel, moving objects and hand gestures, placing a sticker on a ball, putting on socks, fastening shoes, and crawling. You will be video recorded so your performance can be scored after testing. Your name will not be recorded or mentioned on video, and video tapes/files will be used for scoring purposes, stored securely, and destroyed after ten years. Next, you will perform the Kinect analysis phase, which has similar activities to the Shriners Hospital Upper Extremity Evaluation, but performed in front of the Kinect sensor, which records the position of your arms and hands. The Kinect system will not record video, audio, or your name, only the position of your arms and hands. Kinect activities include hand and arm gestures, unscrewing a bottle cap, pulling apart and cutting Play-Doh, throwing ping-pong balls, placing sticker on large ball, putting on socks, and fastening shoe.

DURATION: Your participation will consist of a single visit lasting about 1 hour.

RISKS: The risks associated with this study include risks similar to activities of daily living. You will not be in contact with any electrical or mechanical lab instruments. You will use household objects (including Play-Doh, kitchen utensils, wooden beads, a plastic bottle, paper money and coins, stickers, and ping-pong balls) to simulate these activities of daily living. Another risk may be loss of confidentiality. Every effort will be made to keep your study records confidential, but we cannot guarantee it. Your data will be kept safely in a locked file cabinet and electronic copies on a password-protected computer which will only be accessed by study personnel.

Initials: _____

Page 1 of 3

Date: _____

Protocol Number: HR-2638

BENEFITS: You will receive firsthand exposure to biomechanics research and an opportunity to learn about clinical motion analysis technology. Your participation will help to determine if this motion analysis system is effective. In the future this system may be implemented in clinics to evaluate upper extremity needs of children with disabilities.

CONFIDENTIALITY: All information you reveal in this study will be kept confidential. All your data will be assigned a code number rather than using your name or other information that could identify you. When the results of the study are published, you will not be named. The data will be destroyed by shredding paper documents and deleting electronic files 10 years after the completion of the study. Hard copies of data and video recordings will be stored in locked filing cabinets accessible only to study personnel, and destroyed after ten years. Your research records may be inspected by the Marquette University Institutional Review Board or its designees, and (as allowable by law) state and federal agencies.

COMPENSATION: You will be paid $25.00 for your participation in this study. You will complete W-9 and subject compensation agreement forms at the time of testing. A check will be processed and mailed to the address listed on the forms.

EXTRA COSTS TO PARTICIPATE: You will be responsible for all costs incurred for transportation to Marquette University, including parking.

INJURY OR ILLNESS: Marquette University will not provide medical treatment or financial compensation if you are injured or become ill as a result of participating in this research project. This does not waive any of your legal rights nor release any claim you might have based on negligence.

VOLUNTARY NATURE OF PARTICIPATION: Participating in this study is completely voluntary and you may withdraw from the study and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled. You may withdraw at any time by notifying study personnel of your decision. If you should decide to withdraw, all electronic data related to your testing will be permanently deleted, all hardcopy files shredded, and videotapes erased or destroyed.

CONTACT INFORMATION: If you have any questions about this research project, you can contact Jacob R. Rammer (jacob.rammer@marquette.edu, 414-288-8211) or Dr. Gerald F. Harris (gerald.harris@marquette.edu, 414-288-1586) If you have questions or concerns about your rights as a research participant, you can contact Marquette University's Office of Research Compliance at (414) 288-7570.

Initials: _____

Date: _____

Protocol Number: **HR- 2638**

I HAVE HAD THE OPPORTUNITY TO READ THIS ASSENT FORM, ASK QUESTIONS ABOUT THE RESEARCH PROJECT AND I AM PREPARED TO PARTICIPATE IN THIS PROJECT.

_____   _____
Participant's Signature   Date

_____
Participant's Name

_____   _____
Researcher's Signature   Date

I HAVE HAD THE OPPORTUNITY TO READ THIS CONSENT FORM, ASK QUESTIONS ABOUT THE RESEARCH PROJECT AND I AM PREPARED TO GIVE MY PERMISSION FOR MY CHILD TO PARTICIPATE IN THIS PROJECT.

_____   _____
Parent/Legal Guardian's Signature   Date

_____
Parent/Legal Guardian's Name

_____   _____
Researcher's Signature   Date

MARQUETTE
UNIVERSITY
Be The Difference.

July 22, 2013

Mr. Jacob Rammer
Biomedical Engineering

Dear Mr. Rammer:

Your protocol number HR-2638, titled, *"Partial Automation and Quantitative Enhancement of the "Shriners Hospital for Children Upper Extremity Evaluation" using Microsoft Kinect"* was expedited on July 22, 2013, by a member of the Marquette University Institutional Review Board.

Your IRB approved informed consent form is enclosed with this letter. Use the stamped copies of this form when recruiting research participants. Each research participant should receive a copy of the stamped consent form for their records. Your stamped recruitment flyer is also enclosed; use stamped copies of the flyer for recruiting research participants.

Subjects who go through the consent process are considered enrolled participants and are counted toward the total number of subjects, even if they have no further participation in the study. Please keep this in mind when conducting your research. This study is currently approved for 20 subjects.

If you need to increase the number of subjects, add research personnel, or make any other changes to your protocol you must submit an IRB Protocol Amendment Form, which can be found on the Office of Research Compliance web site: http://www.marquette.edu/researchcompliance/research/irbforms.shtml. All changes must be reviewed and approved by the IRB before being initiated, except when necessary to eliminate apparent immediate hazards to the human subjects. Any public advertising of this project requires prior IRB approval. If there are any adverse events, please notify the Marquette University IRB immediately.

Your approval is valid until July 21, 2014. Prior to this date, you will be contacted regarding continuing IRB review.

An IRB Final Report Form must be submitted once this research project is complete. The form should be submitted in a timely fashion, and must be received no later than the protocol expiration date.

If you have any questions or concerns, please do not hesitate to contact me. Thank you for your time and cooperation.

Sincerely,

Amanda J. Ahrndt, RN, MS, MSN, CIM, CIP
IRB Manager

cc: Dr. Christopher Okunseri, IRB Chair
     Dr. Gerald Harris, BIEN
     Ms. Sherri Lex, Graduate School
     Ms. Cheryl Wanta, OREC

Enclosures (2)

APPENDIX IV: COMPREHENSIVE RESULTS OF KINECT STUDY

ACTIVITY 1: GRASP/RELEASE NEUTRAL
KINEMATIC FOCUS: Finger flexion/extension with wrist in neutral position
KINECT SYSTEM SETUP: Hand kinematics software – whole-hand mode
TESTING PROTOCOL: With the wrist in a neutral position, ask subject to close and open both hands in a repeating pattern to the extent possible. Repeat for 10-20+ cycles and ensure both hands are tracked by software throughout.
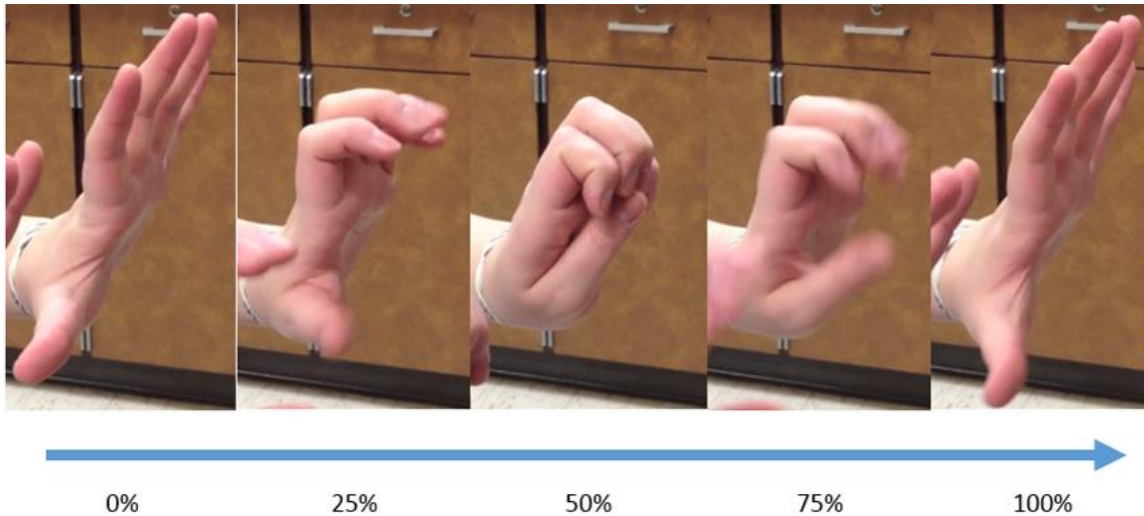
Figure IV.1. Activity Timeline for Grasp/Release Neutral

Table IV.1. Kinect-detected Parameters for Exemplar Subject, Grasp/Release Neutral

Metric	Detected Value
Left hand Finger ROM	78.350°
Left hand Finger Peak Velocity	545.357°/s
Left hand Finger Peak Acceleration	11869.407°/s^2
Right hand Finger ROM	89.538°
Right hand Finger Peak Velocity	576.405°/s
Right hand Finger Peak Acceleration	10612.894°/s^2
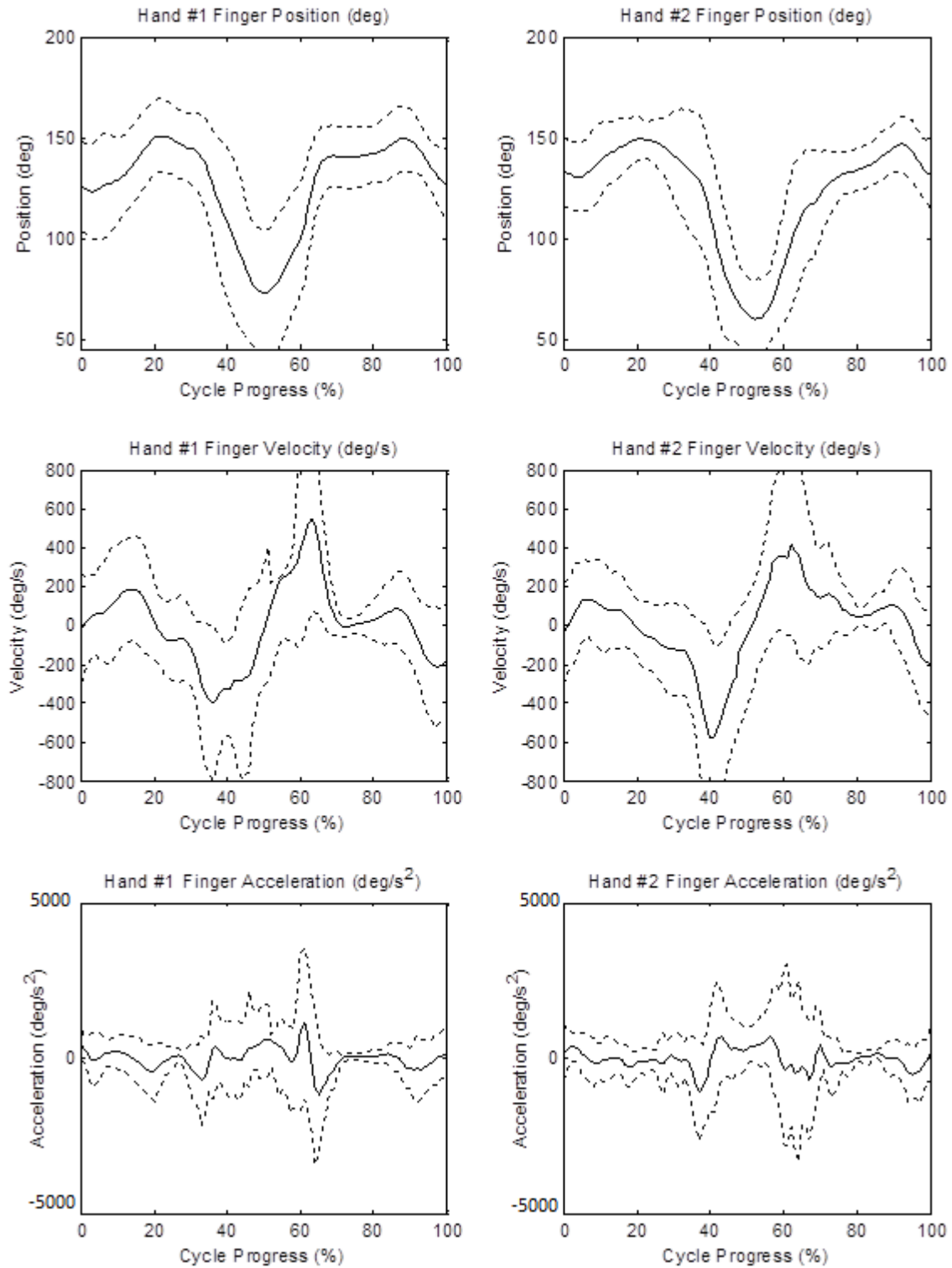
Figure IV.2. Kinematic Plots for Exemplar Subject, Grasp/Release Neutral

Table IV.2. Kinect Normal Population Statistics, Grasp/Release Neutral

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left hand Finger ROM	n=12	31.67°	14.54°	7.58°	57.27°
Left hand Finger Peak Velocity	n=12	154.91°/s	73.72°/s	45.12°/s	273.46°/s
Left hand Finger Peak Acceleration	n=12	6611°/s^2	3582°/s^2	2219°/s^2	12677°/s^2
Right hand Finger ROM	n=12	26.50°	10.83°	8.48°	45.44°
Right hand Finger Peak Velocity	n=12	153.87°/s	97.79°/s	61.07°/s	364.42°/s
Right hand Finger Peak Acceleration	n=12	6805°/s^2	4577°/s^2	2139°/s^2	15667°/s^2

Table IV.3. Correlation Statistics, Grasp/Release Neutral – Finger Component

Spearman Correlation Coefficients	Left hand Finger ROM	Left hand Finger Peak Velocity	Left hand Finger Peak Acceleration	Right hand Finger ROM	Right hand Finger Peak Velocity	Right hand Finger Peak Acceleration
Left hand Finger ROM	1.00000					
Left hand Finger Peak Velocity	0.85495	1.00000				
Left hand Finger Peak Acceleration	0.81978	0.89890	1.00000			
Right hand Finger ROM	0.43956	0.41758	0.54396	1.00000		
Right hand Finger Peak Velocity	0.41758	0.47253	0.66484	0.60440	1.00000	
Right hand Finger Peak Acceleration	0.59341	0.59890	0.79670	0.46703	0.83516	1.00000

n=12; data converted to logarithmic scale prior to analysis

Figure IV.3. Correlation Plot for Normal Population, Grasp/Release Neutral

ACTIVITY 2: GRASP/RELEASE FLEXED
KINEMATIC FOCUS: Finger flexion/extension with wrist in flexed position
KINECT SYSTEM SETUP: Hand kinematics software – whole-hand mode
TESTING PROTOCOL: With the wrist in a flexed position, ask subject to close and open both hands in a repeating pattern to the extent possible. Repeat for 10-20+ cycles and ensure both hands are tracked by software throughout.

0%   25%   50%   75%   100%
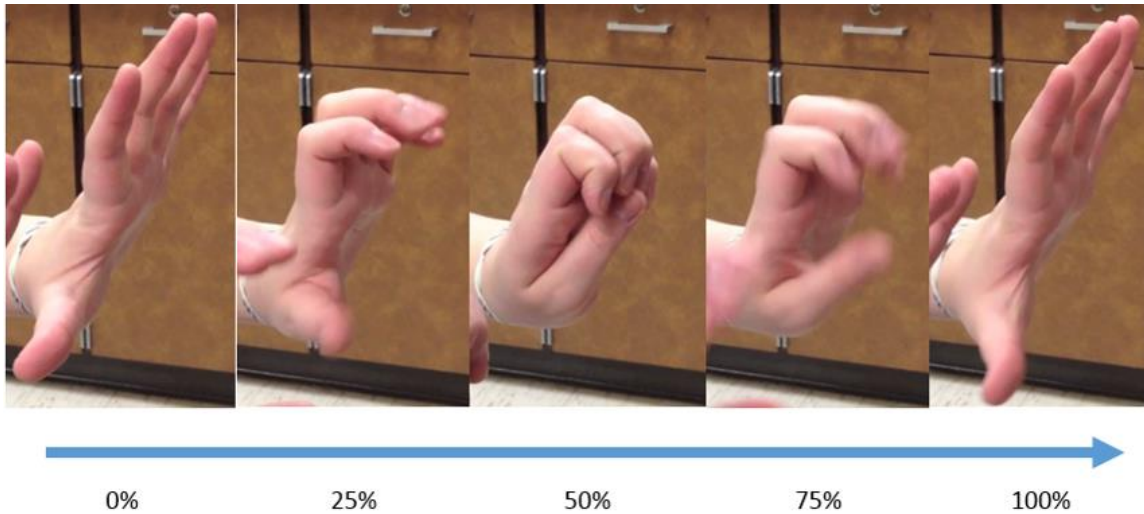
Figure IV.4. Activity Timeline for Grasp/Release Flexed

Table IV.4. Kinect-detected Parameters for Exemplar Subject, Grasp/Release Flexed

Metric	Detected Value
Left hand Finger ROM	82.654°
Left hand Finger Peak Velocity	544.900°/s
Left hand Finger Peak Acceleration	8382.342°/s^2
Right hand Finger ROM	92.225°
Right hand Finger Peak Velocity	534.010°/s
Right hand Finger Peak Acceleration	8522.801°/s^2

Figure IV.5. Kinematic Plots for Exemplar Subject, Grasp/Release Flexed

Table IV.5. Kinect Normal Population Statistics, Grasp/Release Flexed

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left hand Finger ROM	n=12	35.96°	22.39°	14.44°	79.68°
Left hand Finger Peak Velocity	n=12	150.82°/s	34.86°/s	105.68°/s	203.36°/s
Left hand Finger Peak Acceleration	n=12	8413°/s^2	4702°/s^2	4234°/s^2	15963°/s^2
Right hand Finger ROM	n=12	26.87°	16.55°	12.40°	62.12°
Right hand Finger Peak Velocity	n=12	137.49°/s	46.86°/s	62.94°/s	194.89°/s
Right hand Finger Peak Acceleration	n=12	6820°/s^2	3211°/s^2	2280°/s^2	10766°/s^2

Table IV.6. Correlation Statistics, Grasp/Release Flexed – Finger Component

Spearman Correlation Coefficients	Left hand Finger ROM	Left hand Finger Peak Velocity	Left hand Finger Peak Acceleration	Right hand Finger ROM	Right hand Finger Peak Velocity	Right hand Finger Peak Acceleration
Left hand Finger ROM	1.00000					
Left hand Finger Peak Velocity	0.03571	1.00000				
Left hand Finger Peak Acceleration	-0.14286	0.71429	1.00000			
Right hand Finger ROM	0.39286	0.57143	0.21429	1.00000		
Right hand Finger Peak Velocity	0.07143	0.39286	0.21429	0.75000	1.00000	
Right hand Finger Peak Acceleration	0.46429	0.71429	0.75000	0.67857	0.46429	1.00000

n=7; outliers removed; data converted to logarithmic scale prior to analysis
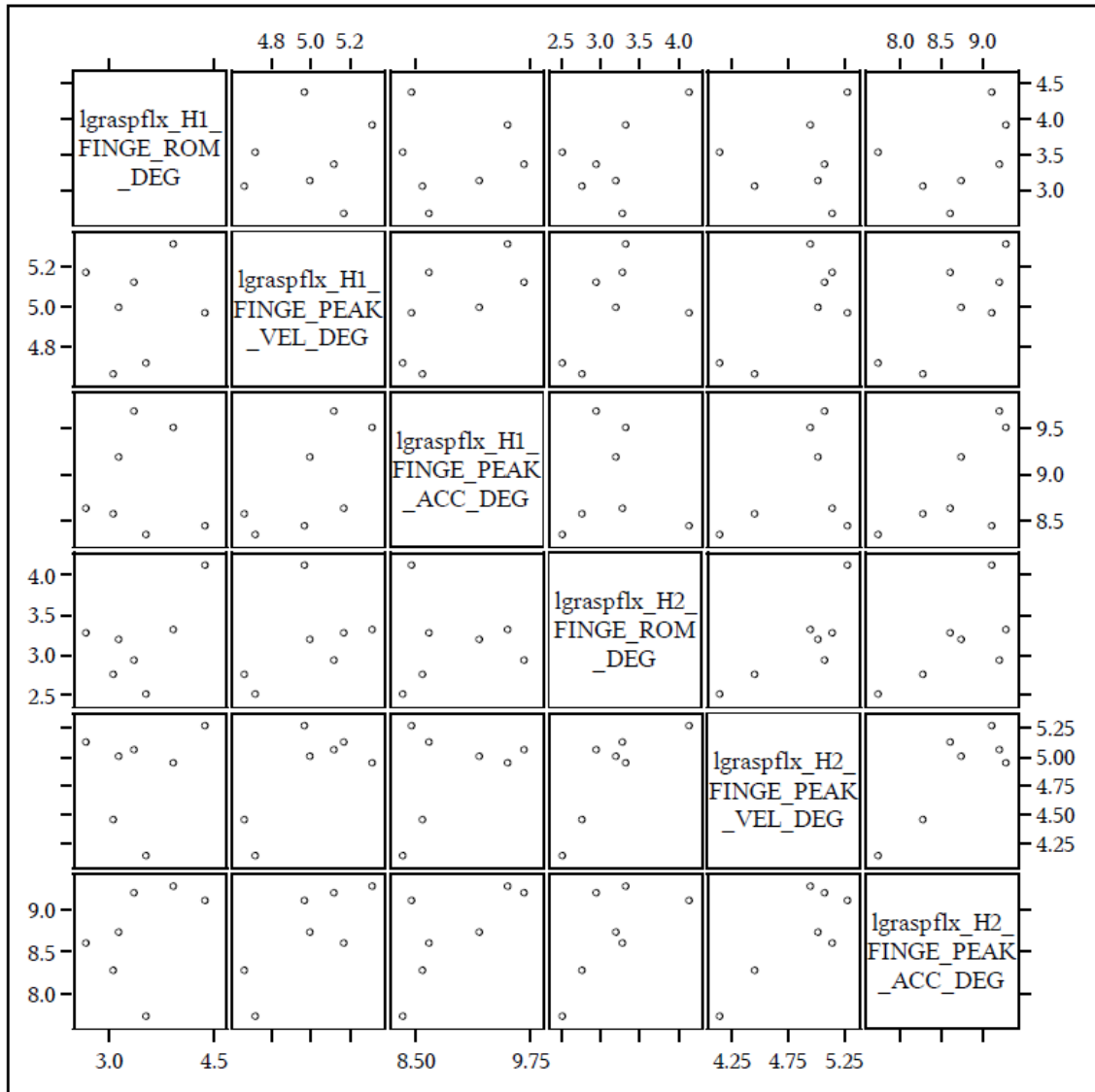
Figure IV.6. Correlation Plot for Normal Population, Grasp/Release Flexed

ACTIVITY 3: GRASP/RELEASE EXTENDED
KINEMATIC FOCUS: Finger flexion/extension with wrist in extended position
KINECT SYSTEM SETUP: Hand kinematics software – whole-hand mode
TESTING PROTOCOL: With the wrist in an extended position, ask subject to close and open
both hands in a repeating pattern to the extent possible. Repeat for 10-20+ cycles and ensure both
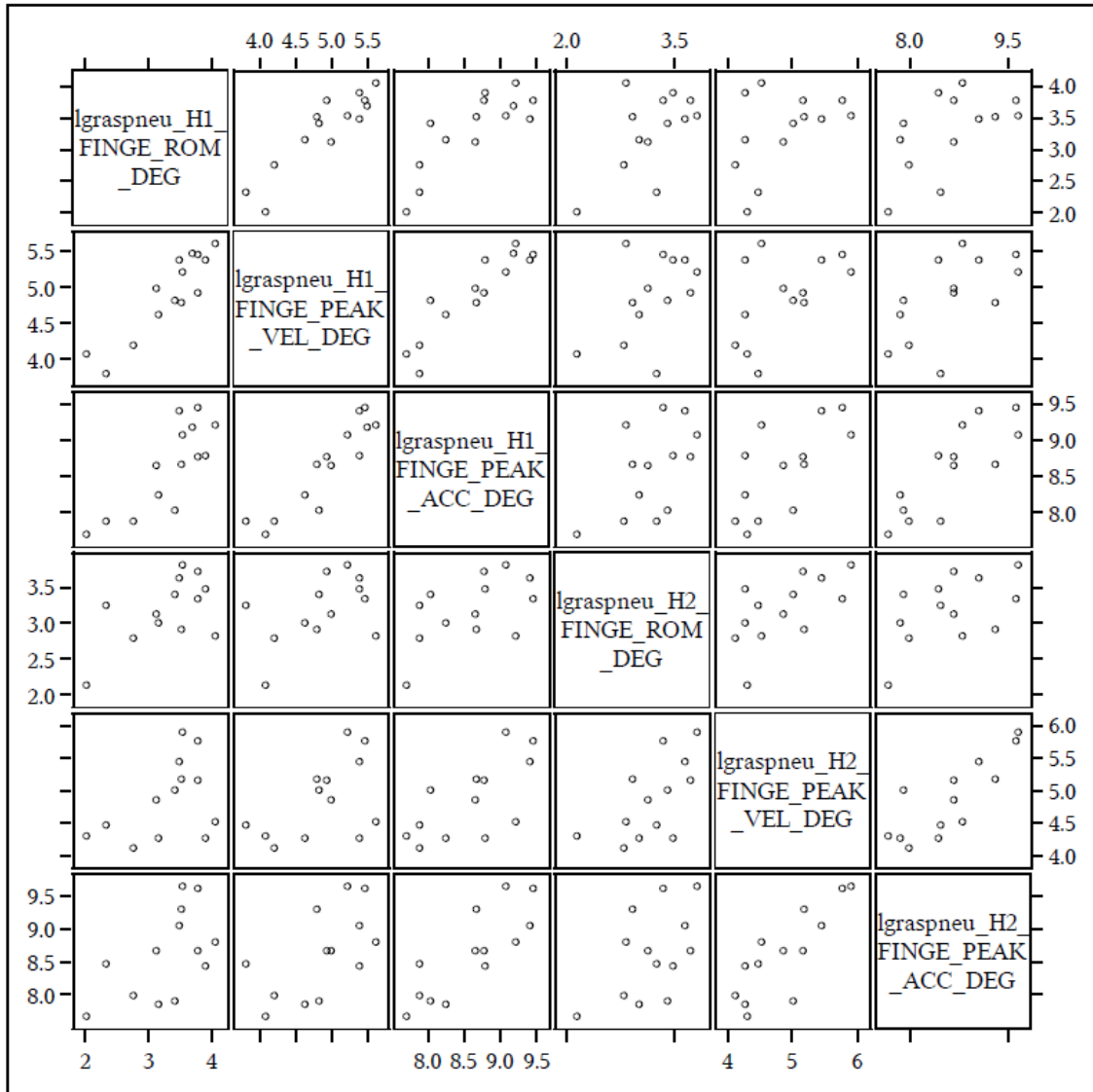hands are tracked by software throughout.
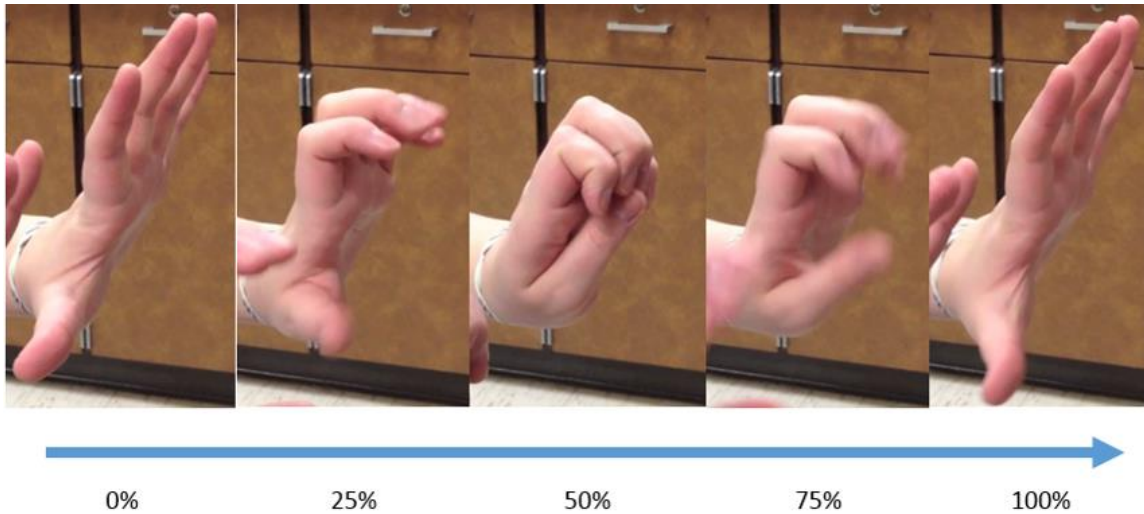
Figure IV.7. Activity Timeline for Grasp/Release Extended

Table IV.7. Kinect-detected Parameters for Exemplar Subject, Grasp/Release Extended

Metric	Detected Value
Left hand Finger ROM	70.647°
Left hand Finger Peak Velocity	385.191°/s
Left hand Finger Peak Acceleration	7406.780°/s^2
Right hand Finger ROM	49.297°
Right hand Finger Peak Velocity	272.700°/s
Right hand Finger Peak Acceleration	6424.106°/s^2
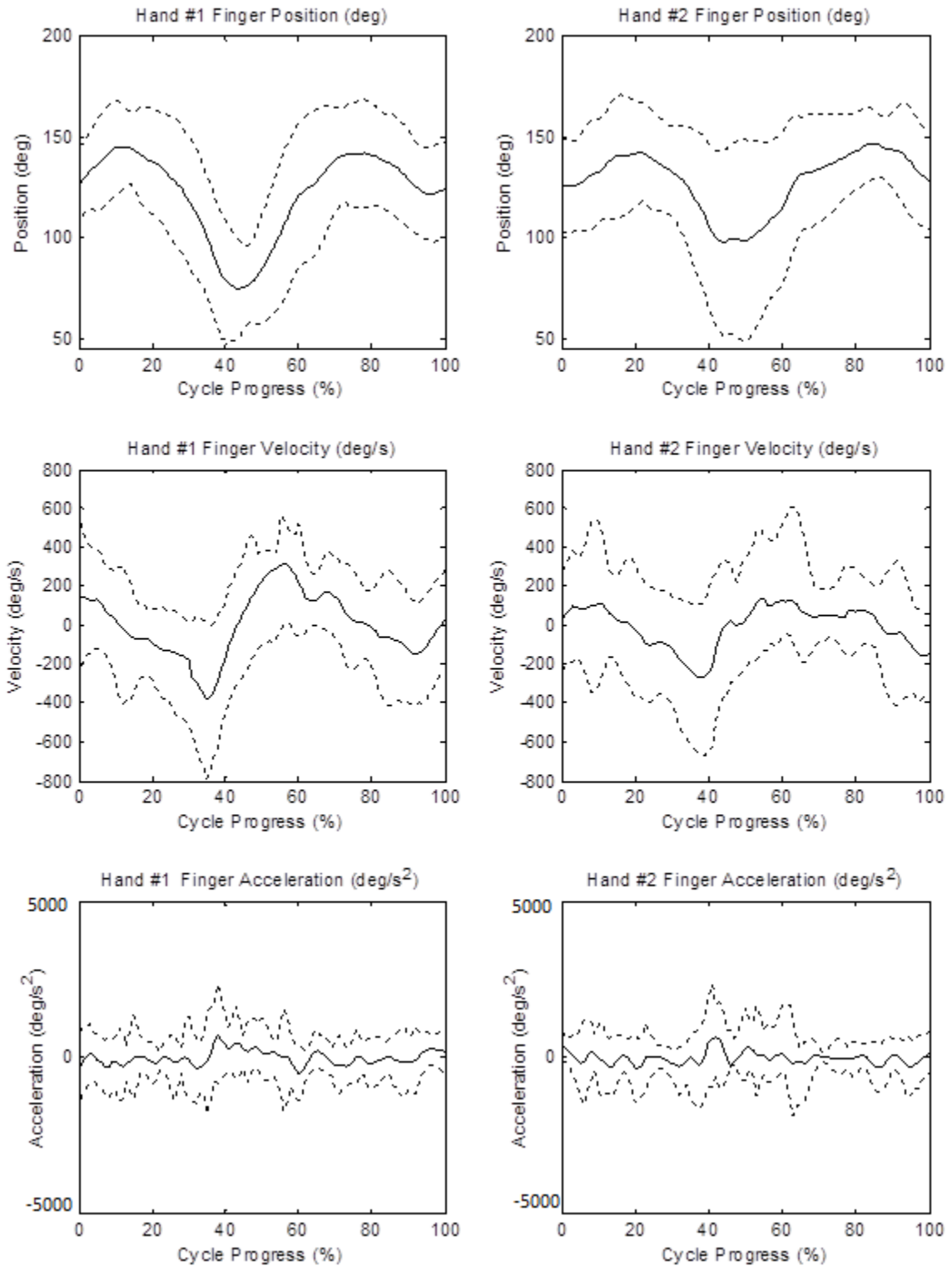
Figure IV.8. Kinematic Plots for Exemplar Subject, Grasp/Release Extended

Table IV.8. Kinect Normal Population Statistics, Grasp/Release Extended

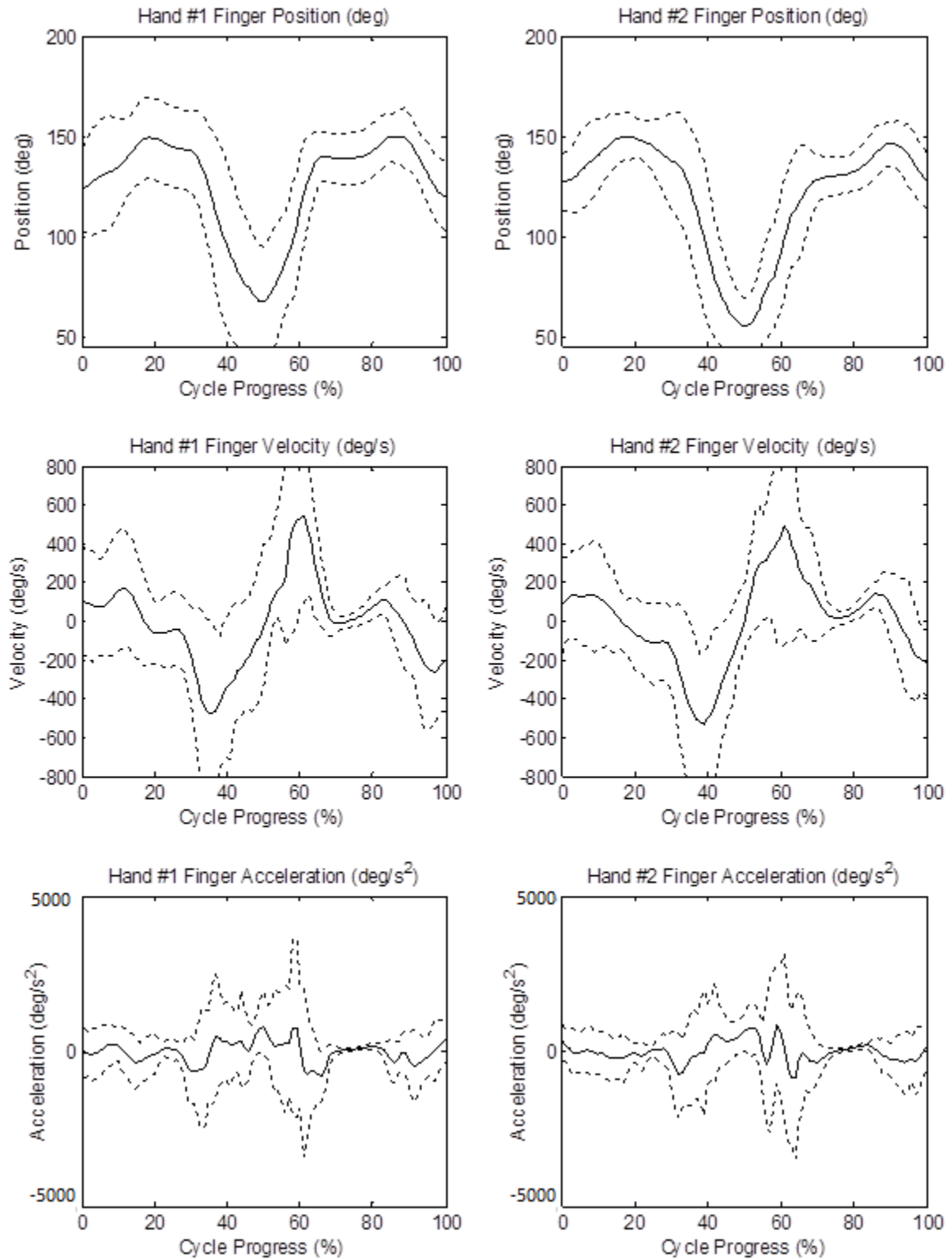| Metric	n	Mean	Std Dev.	Minimum	Maximum
Left hand Finger ROM	n=12	28.20°	11.80°	10.02°	58.99°
Left hand Finger Peak Velocity	n=12	194.03°/s	89.07°/s	92.84°/s	398.98°/s
Left hand Finger Peak Acceleration	n=12	8492°/s^2	4639°/s^2	2750°/s^2	19571°/s^2
Right hand Finger ROM	n=12	27.10°	12.80°	6.91°	56.40°
Right hand Finger Peak Velocity	n=12	149.55°/s	87.58°/s	63.39°/s	372.31°/s
Right hand Finger Peak Acceleration	n=12	6112°/s^2	3055°/s^2	1983°/s^2	12877°/s^2

Table IV.9. Correlation Statistics, Grasp/Release Extended – Finger Component

Spearman Correlation Coefficients	Left hand Finger ROM	Left hand Finger Peak Velocity	Left hand Finger Peak Acceleration	Right hand Finger ROM	Right hand Finger Peak Velocity	Right hand Finger Peak Acceleration
Left hand Finger ROM	1.00000					
Left hand Finger Peak Velocity	0.49011	1.00000				
Left hand Finger Peak Acceleration	-0.07692	0.73187	1.00000			
Right hand Finger ROM	0.32747	0.52967	0.37143	1.00000		
Right hand Finger Peak Velocity	0.47253	0.53407	0.26154	0.63516	1.00000	
Right hand Finger Peak Acceleration	0.41099	0.72747	0.55165	0.21758	0.62198	1.00000

n=12; data converted to logarithmic scale prior to analysis
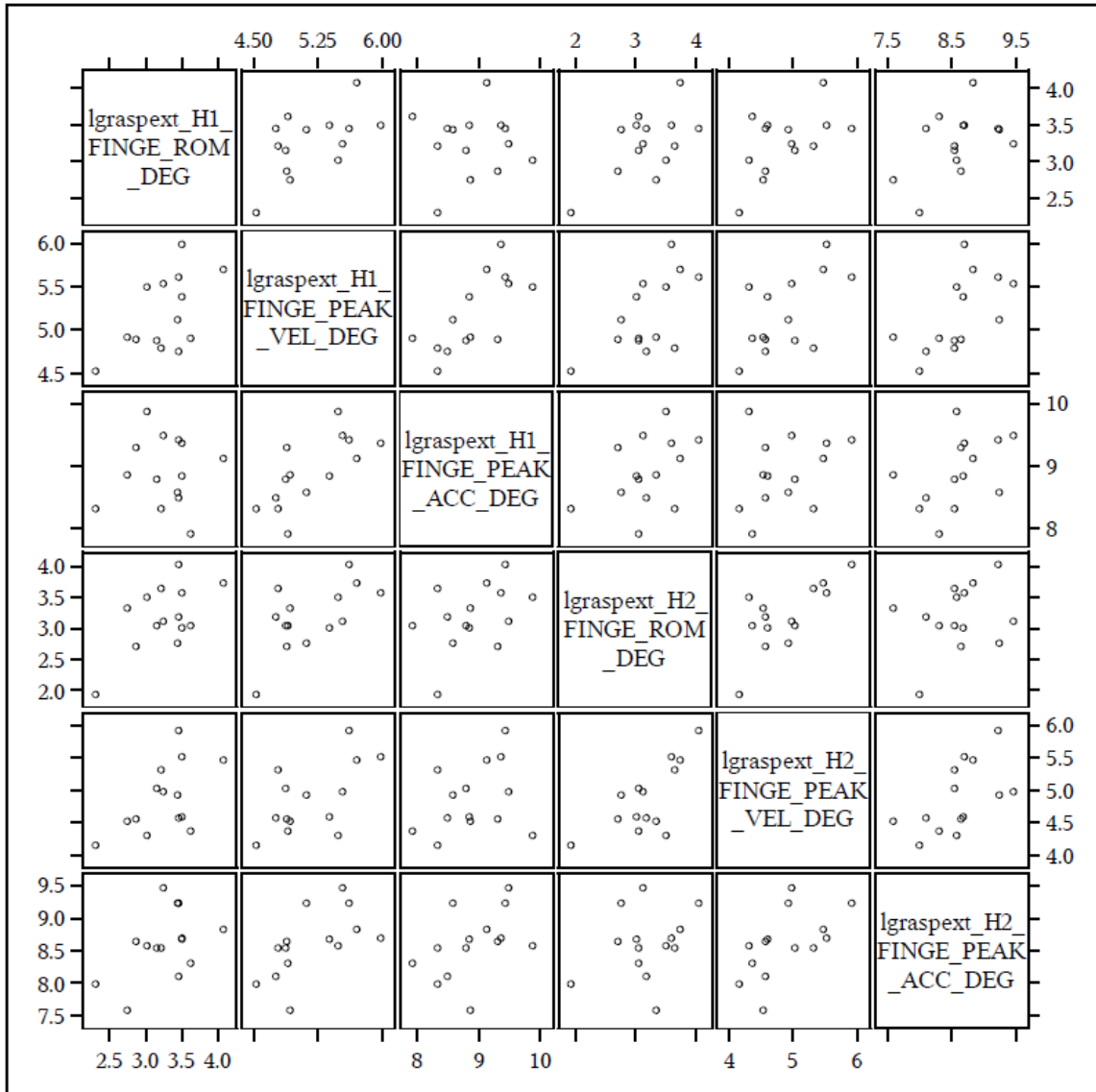
Figure IV.9. Correlation Plot for Normal Population, Grasp/Release Extended

ACTIVITY 4: THUMB-INDEX PINCH
KINEMATIC FOCUS: Isolated thumb and index finger flexion/extension
KINECT SYSTEM SETUP: Hand kinematics software – two-finger mode
TESTING PROTOCOL: Instruct subject to hold hands with palms facing Kinect with both hands
fully tracked by software, and pinch thumb and index finger in a repeating pattern as if grasping
and releasing an object to the extent possible. Repeat for 10-20+ cycles and ensure both hands are
tracked by software throughout.

0%   25%   50%   75%   100%
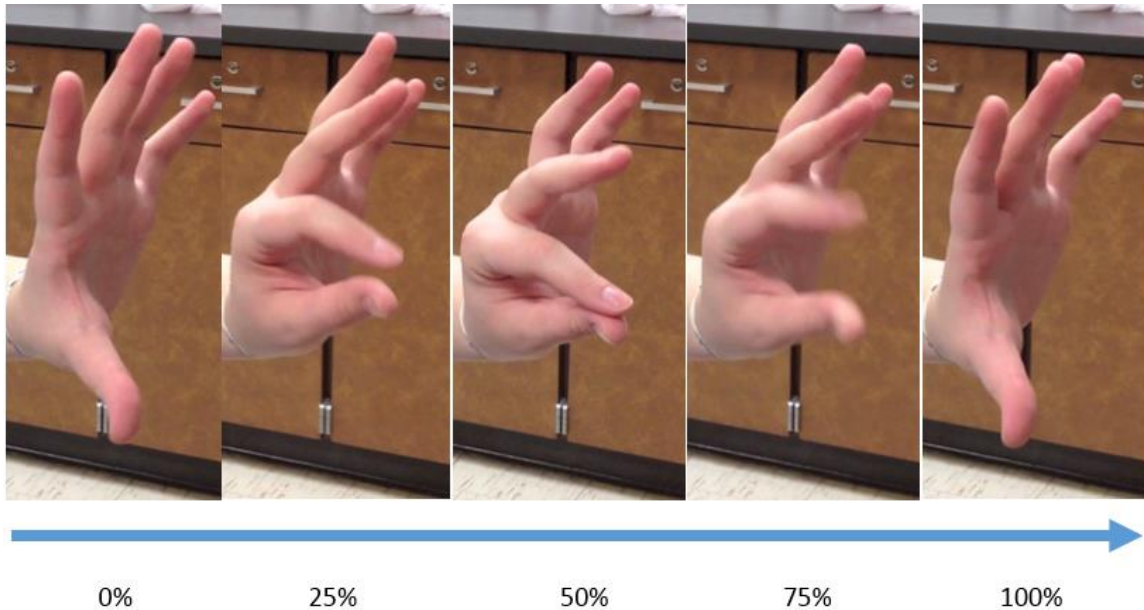
Figure IV.10. Activity Timeline for Thumb-Index Pinch

Table IV.10. Kinect-detected Parameters for Exemplar Subject, Thumb-Index Pinch

Metric	Detected Value
Left hand Index Finger ROM	54.788°
Left hand Index Finger Peak Velocity	276.219°/s
Left hand Index Finger Peak Acceleration	5079.587°/s^2
Right hand Index Finger ROM	36.4748°
Right hand Index Finger Peak Velocity	245.436°/s
Right hand Index Finger Peak Acceleration	9941.303°/s^2
Left hand Thumb ROM	32.655°
Left hand Thumb Peak Velocity	287.889°/s

Left hand Thumb Peak Acceleration	8354.616°/s^2
Right hand Thumb ROM	24.051°
Right hand Thumb Peak Velocity	208.366°/s
Right hand Thumb Peak Acceleration	6911.197°/s^2
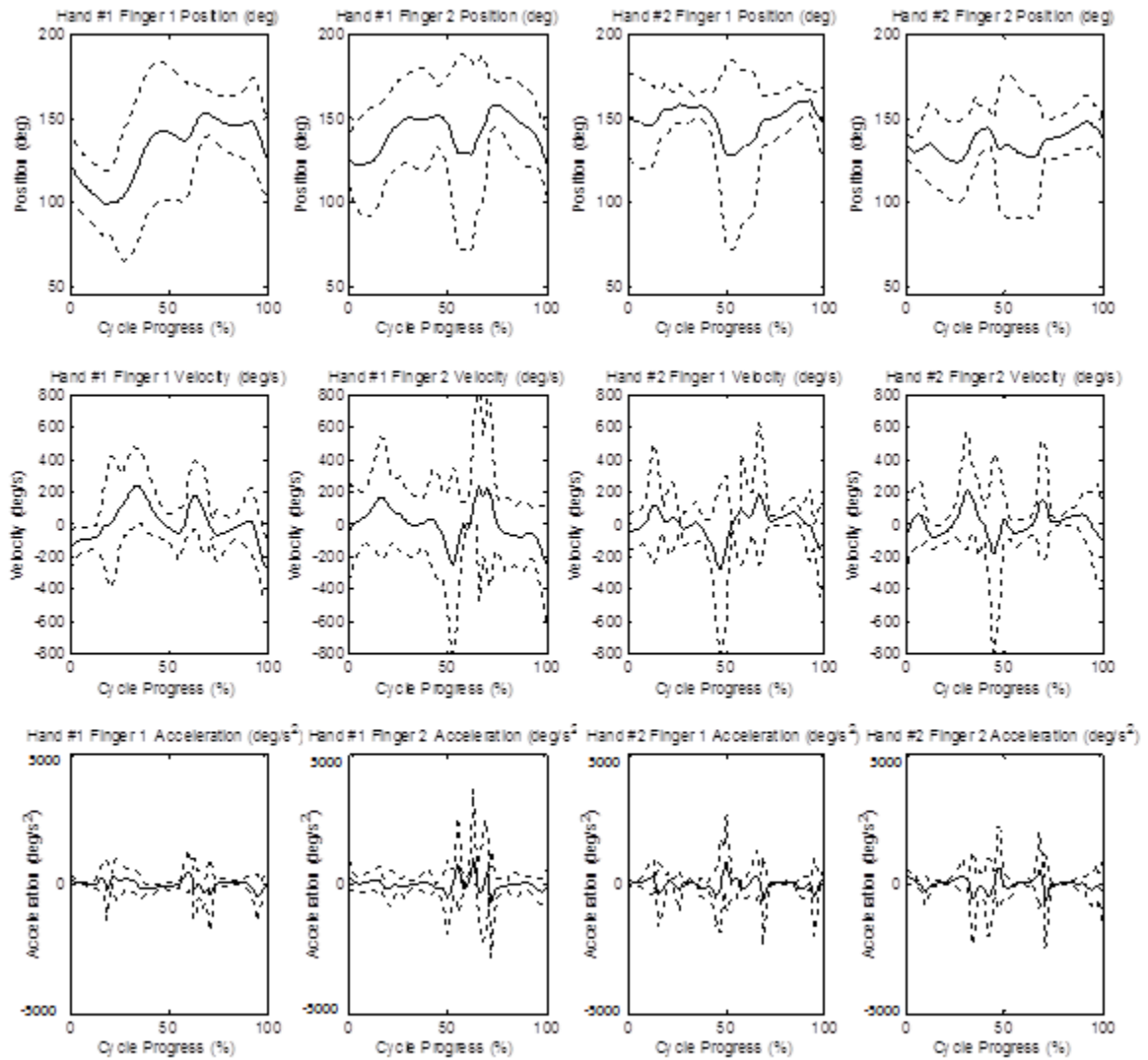
Figure IV.11. Kinematic Plots for Exemplar Subject, Thumb-Index Pinch

Table IV.11. Kinect Normal Population Statistics, Thumb-Index Pinch

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left hand Index Finger ROM	n=12	36.21°	12.86°	22.06°	68.95°
Left hand Index Finger Peak Velocity	n=12	216.63°/s	68.41°/s	115.82°/s	311.66°/s
Left hand Index Finger Peak Acceleration	n=12	12640°/s²	4988°/s²	4957°/s²	21827°/s²
Right hand Index Finger ROM	n=12	33.48°	12.97°	18.75°	64.13°
Right hand Index Finger Peak Velocity	n=12	236.45°/s	90.71°/s	103.32°/s	405.28°/s
Right hand Index Finger Peak Acceleration	n=12	11652°/s²	3842°/s²	5560°/s²	17197°/s²
Left hand Thumb ROM	n=12	28.67°	11.62°	15.18°	53.30°
Left hand Thumb Peak Velocity	n=12	193.74°/s	87.22°/s	67.49°/s	392.10°/s
Left hand Thumb Peak Acceleration	n=12	12273°/s²	5897°/s²	4817°/s²	24167°/s²
Right hand Thumb ROM	n=12	26.52°	14.56°	11.18°	70.72°
Right hand Thumb Peak Velocity	n=12	216.55°/s	94.55°/s	135.01°/s	425.66°/s
Right hand Thumb Peak Acceleration	n=12	12863°/s²	6380°/s²	5453°/s²	24438°/s²

Table IV.12. Correlation Statistics, Thumb/Index Pinch – Left Hand Component

Spearman Correlation Coefficients	Left Index Finger ROM	Left Index Finger Peak Velocity	Left Index Finger Peak Acceleration	Left Thumb ROM	Left Thumb Peak Velocity	Left Thumb Peak Acceleration
Left Index Finger ROM	1.00000					
Left Index Finger Peak Velocity	0.44505	1.00000				
Left Index Finger Peak Acceleration	0.36264	0.75275	1.00000			
Left Thumb ROM	0.75824	0.54945	0.50000	1.00000		
Left Thumb Peak Velocity	0.48252	0.41958	0.62937	0.67832	1.00000	
Left Thumb Peak Acceleration	0.38462	0.24476	0.51049	0.35664	0.76923	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.13. Correlation Statistics, Thumb/Index Pinch – Right Hand Component

Spearman Correlation Coefficients	Right Index Finger ROM	Right Index Finger Peak Velocity	Right Index Finger Peak Acceleration	Right Thumb ROM	Right Thumb Peak Velocity	Right Thumb Peak Acceleration
Right Index Finger ROM	1.00000					
Right Index Finger Peak Velocity	0.79670	1.00000				
Right Index Finger Peak Acceleration	0.58242	0.64835	1.00000			
Right Thumb ROM	0.47802	0.24725	0.48901	1.00000		
Right Thumb Peak Velocity	0.63187	0.51099	0.78571	0.51648	1.00000	
Right Thumb Peak Acceleration	0.23626	0.42308	0.60989	0.29670	0.54945	1.00000

n=12; data converted to logarithmic scale prior to analysis
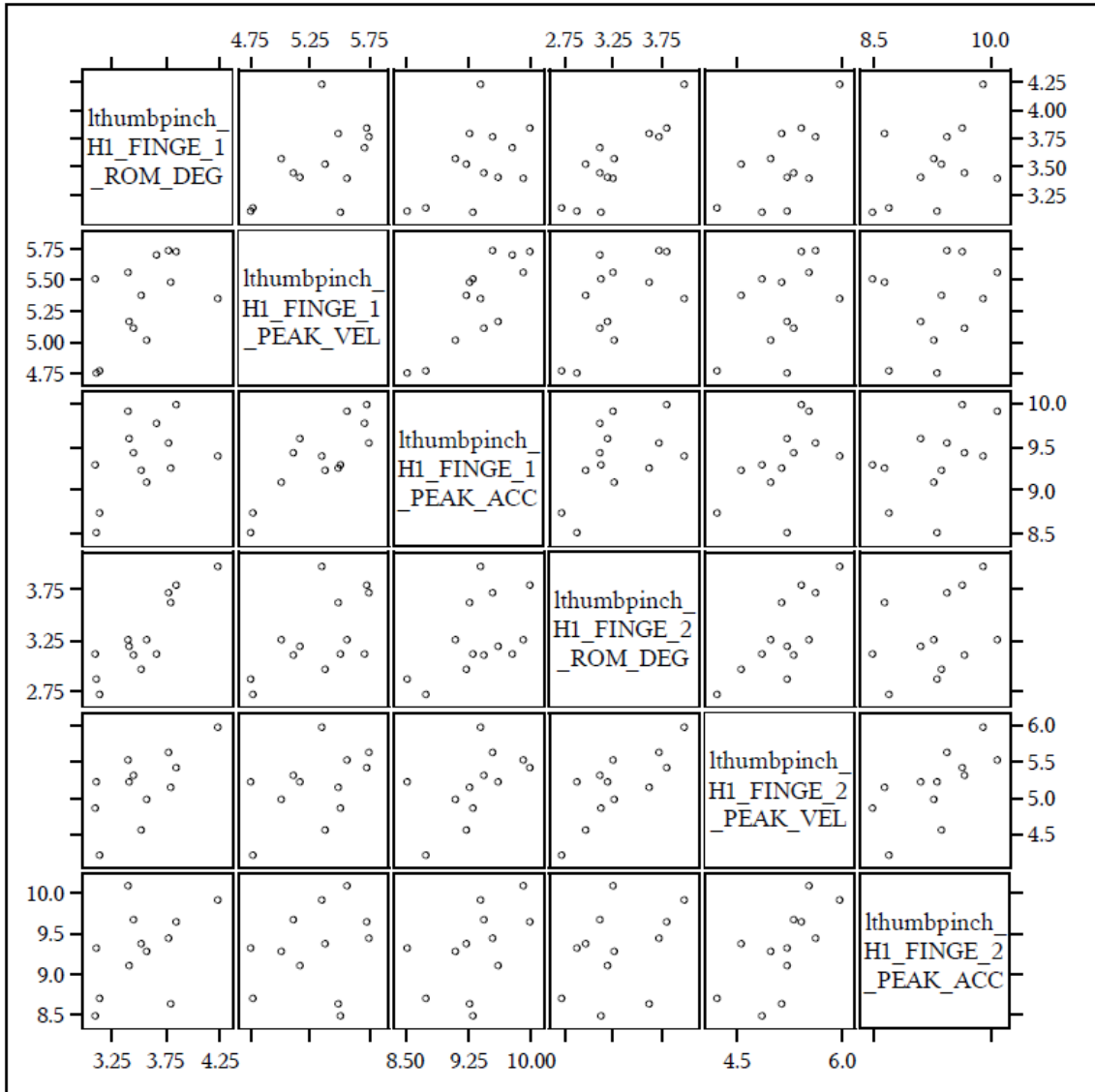
Figure IV.12. Correlation Plot for Normal Population, Thumb-Index Pinch, Left Hand
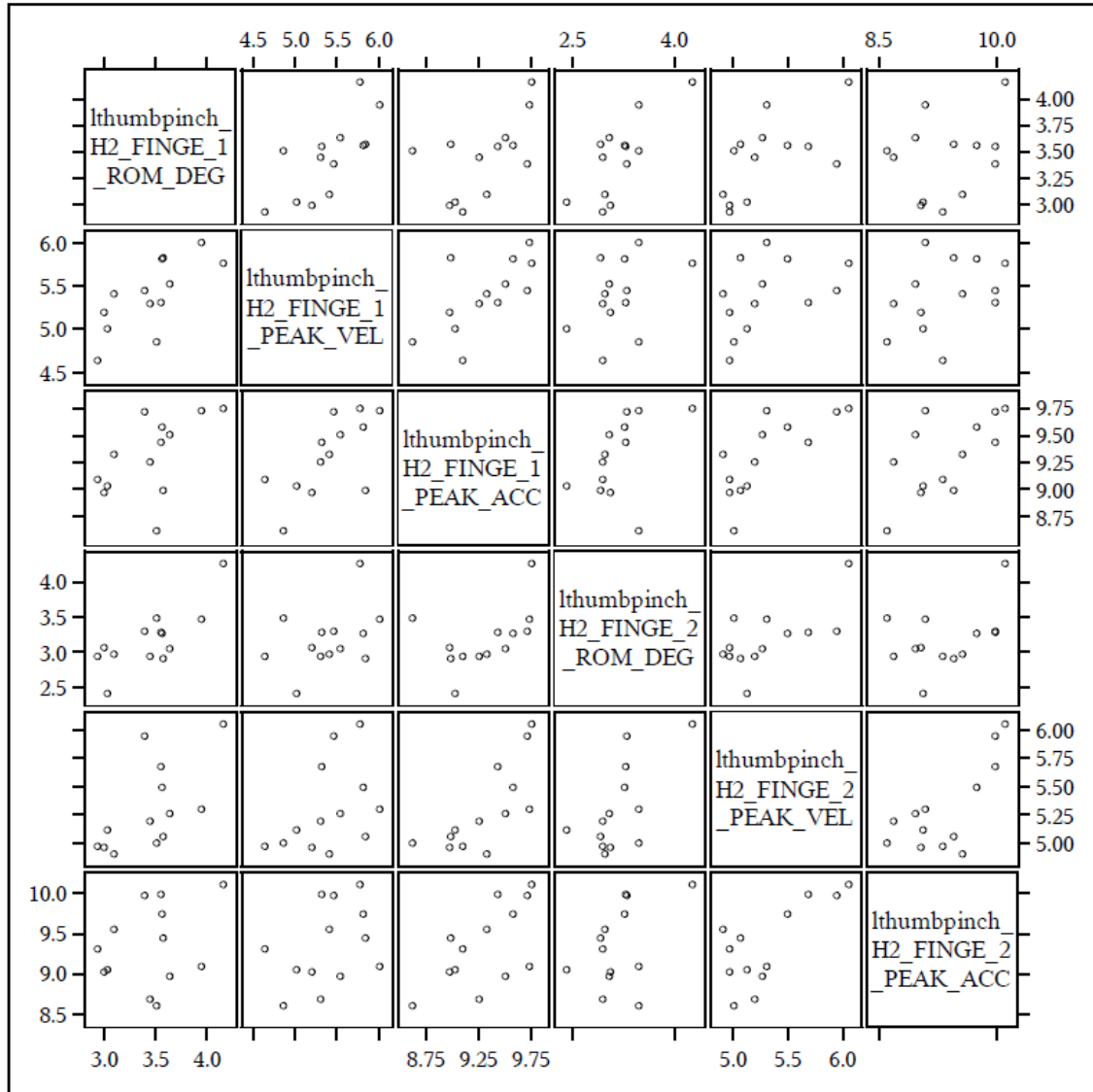
Figure IV.13. Correlation Plot for Normal Population, Thumb-Index Pinch, Right Hand

ACTIVITY 5: WRIST RANGE OF MOTION
KINEMATIC FOCUS: Wrist flexion/extension
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: Instruct subject to hold both arms outward at sides, with palms facing
upward, and flex and extend the wrist to the extent possible in a repeating pattern. Repeat for 10-
20+ cycles and ensure both arms are tracked fully by the software throughout.
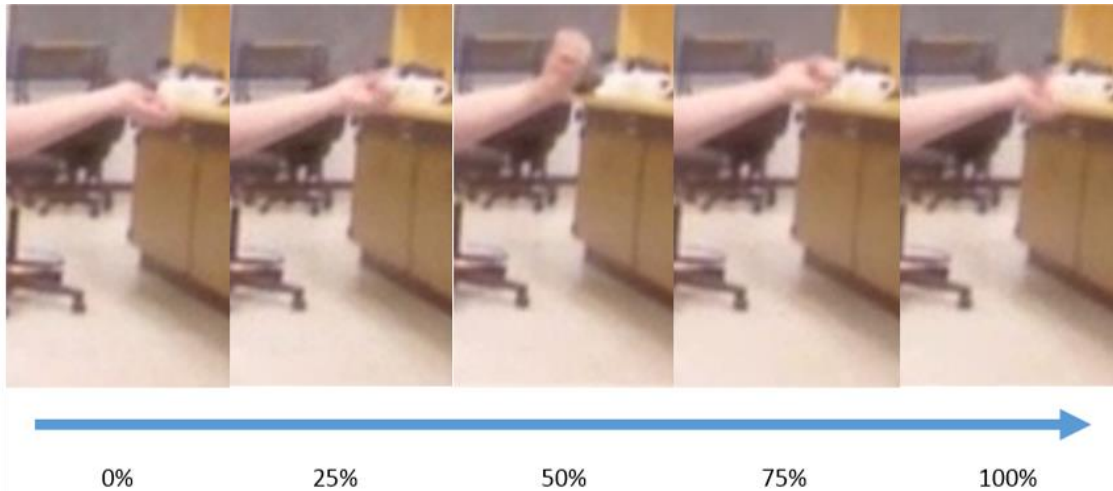
Figure IV.14. Activity Timeline for Wrist Range of Motion

Table IV.14. Kinect-detected Parameters for Exemplar Subject, Wrist Range of Motion

Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	48.031°	Right Wrist ROM	33.697°
Left Wrist Peak Velocity	199.769°/s	Right Wrist Peak Velocity	135.385°/s
Left Wrist Peak Acceleration	2203.883°/s^2	Right Wrist Peak Acceleration	1996.535°/s^2
Left Elbow ROM	29.229°	Right Elbow ROM	29.600°
Left Elbow Peak Velocity	73.120°/s	Right Elbow Peak Velocity	64.575°/s
Left Elbow Peak Acceleration	341.465°/s^2	Right Elbow Peak Acceleration	376.615°/s^2
Left Shoulder ROM	0.346°	Right Shoulder ROM	1.686°
Left Shoulder Peak Velocity	1.458°/s	Right Shoulder Peak Velocity	9.573°/s
Left Shoulder Peak Acceleration	13.007°/s^2	Right Shoulder Peak Acceleration	74.848°/s^2
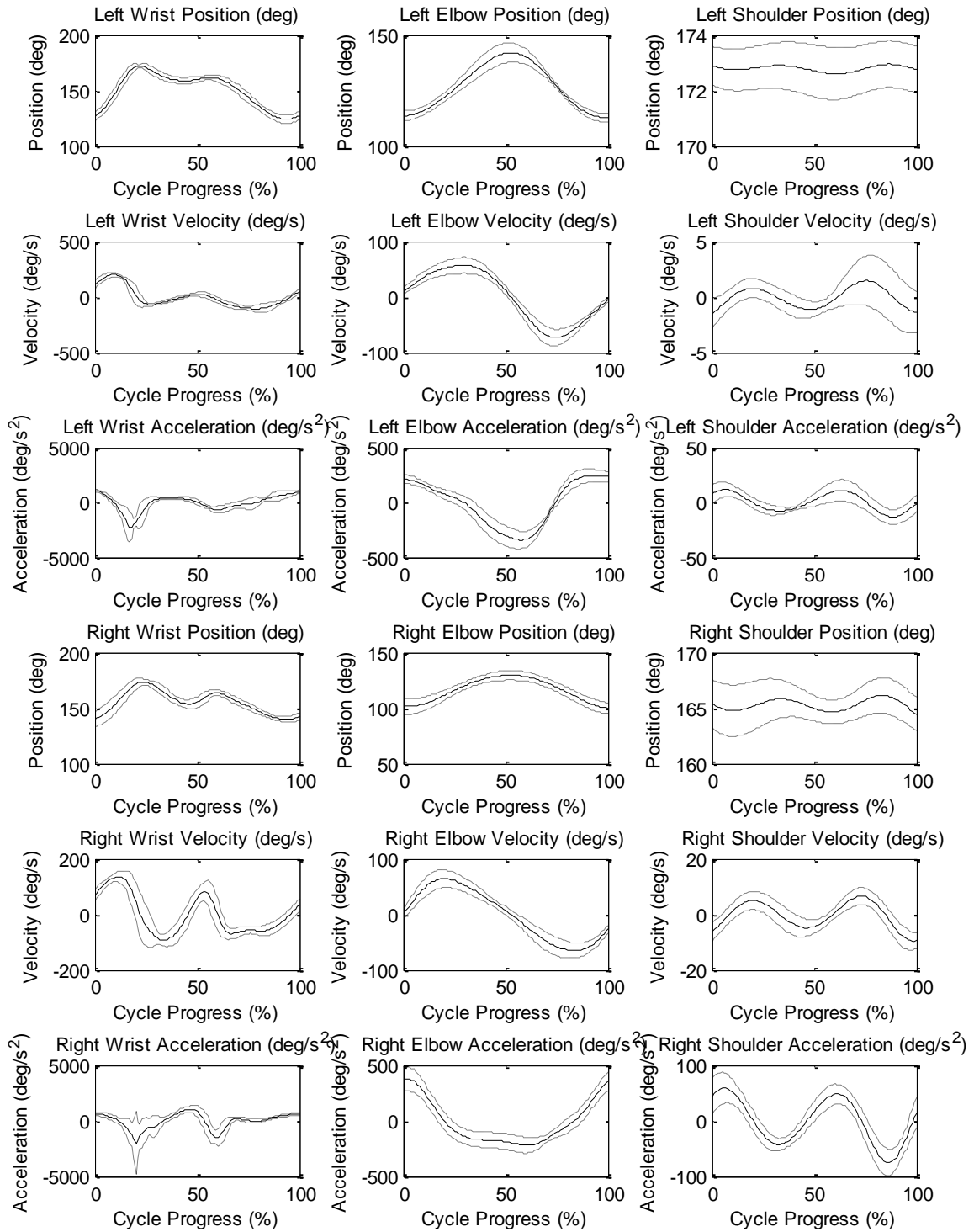
Figure IV.15. Kinematic Plots for Exemplar Subject, Wrist Range of Motion

Table IV.15. Kinect Normal Population Statistics, Wrist Range of Motion

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	25.07°	9.14°	14.69°	47.97°
Left Wrist Peak Velocity	n=12	138.59°/s	77.06°/s	39.08°/s	330.07°/s
Left Wrist Peak Acceleration	n=12	6262°/s^2	7513°/s^2	1044°/s^2	30334°/s^2
Left Elbow ROM	n=12	14.01°	8.02°	0.39°	29.20°
Left Elbow Peak Velocity	n=12	59.21°/s	51.16°/s	2.63°/s	215.36°/s
Left Elbow Peak Acceleration	n=12	2261°/s^2	3302°/s^2	44.40°/s^2	12163°/s^2
Left Shoulder ROM	n=12	2.27°	1.95°	0.71°	7.68°
Left Shoulder Peak Velocity	n=12	11.11°/s	10.24°/s	1.81°/s	141.34°/s
Left Shoulder Peak Acceleration	n=12	540.73°/s^2	751.13°/s^2	28.21°/s^2	2208°/s^2
Right Wrist ROM	n=12	24.27°	12.63°	5.30°	54.19°
Right Wrist Peak Velocity	n=12	141.98°/s	120.18°/s	39.97°/s	532.17°/s
Right Wrist Peak Acceleration	n=12	5468°/s^2	6354°/s^2	1569°/s^2	26401°/s^2
Right Elbow ROM	n=12	14.15°	9.73°	13.14°	33.19°
Right Elbow Peak Velocity	n=12	75.42°/s	80.23°/s	17.69°/s	283.15°/s
Right Elbow Peak Acceleration	n=12	3002°/s^2	3325°/s^2	385.94°/s^2	10135°/s^2
Right Shoulder ROM	n=12	4.19°	4.54°	0.39°	13.57°
Right Shoulder Peak Velocity	n=12	34.46°/s	48.32°/s	1.81°/s	141.34°/s
Right Shoulder Peak Acceleration	n=12	2698°/s^2	5759°/s^2	7.96°/s^2	21515°/s^2

Table IV.16. Correlation Statistics, Wrist ROM – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.30110	1.00000				
Left Wrist Peak Velocity	0.67033	-0.03736	1.00000			
Right Wrist Peak Velocity	0.42857	0.53407	0.27033	1.00000		
Left Wrist Peak Acceleration	0.52967	-0.17363	0.77143	0.09890	1.00000	
Right Wrist Peak Acceleration	0.34945	0.10330	0.24835	0.33187	0.31868	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.17. Correlation Statistics, Wrist ROM – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	0.72747	1.00000				
Left Elbow Peak Velocity	0.75385	0.62637	1.00000			
Right Elbow Peak Velocity	0.36703	0.74505	0.61319	1.00000		
Left Elbow Peak Acceleration	0.41538	0.27473	0.74066	0.48571	1.00000	
Right Elbow Peak Acceleration	0.09011	0.28352	0.49011	0.70110	0.71429	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.18. Correlation Statistics, Wrist ROM – Shoulder Component

Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	0.41538	1.00000				
Left Shoulder Peak Velocity	0.86374	0.59121	1.00000			
Right Shoulder Peak Velocity	0.56044	0.89451	0.71868	1.00000		
Left Shoulder Peak Acceleration	0.89011	0.64835	0.94286	0.77143	1.00000	
Right Shoulder Peak Acceleration	0.52088	0.80659	0.67473	0.96923	0.73187	1.00000

n=12; data converted to logarithmic scale prior to analysis
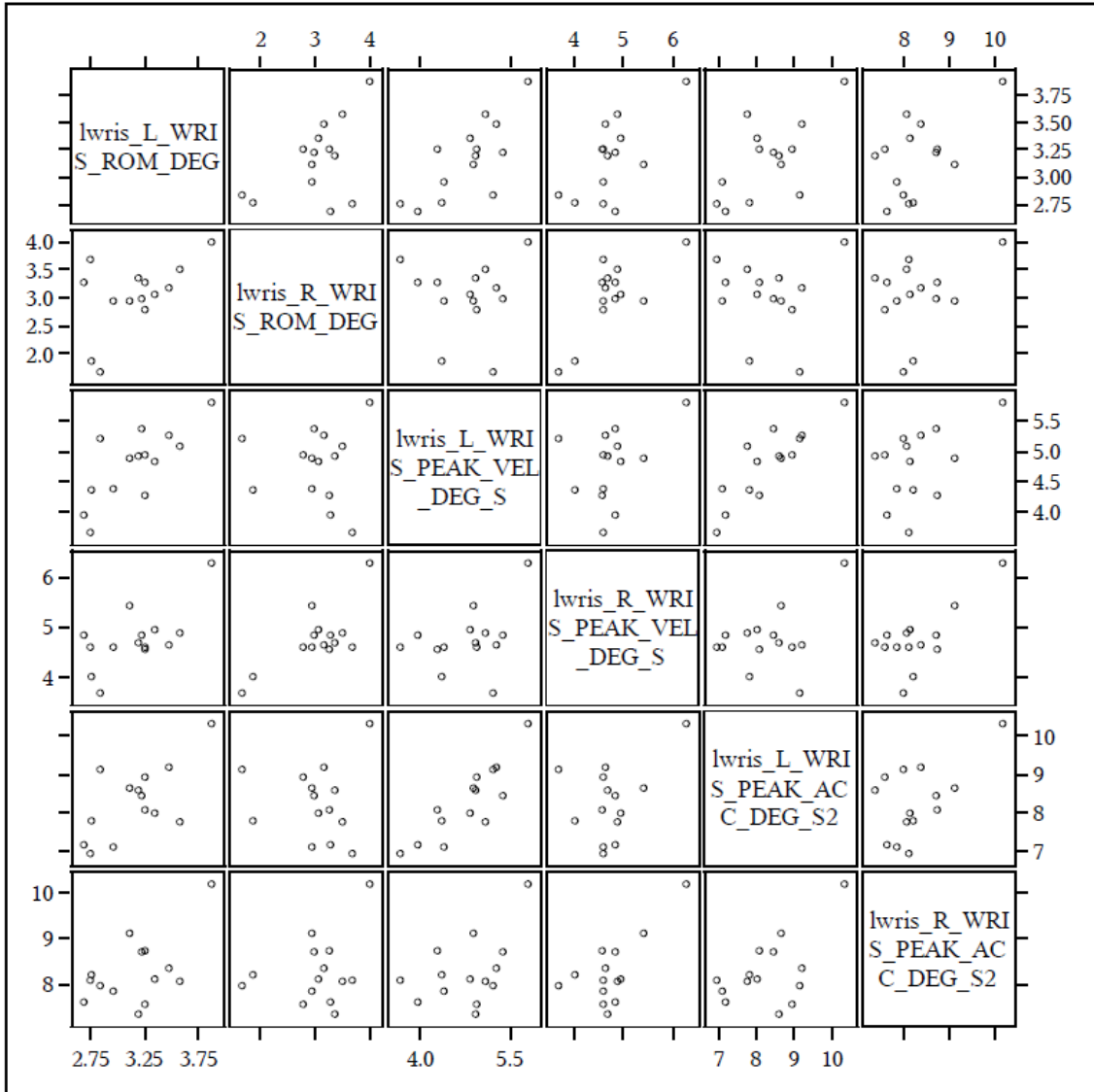
Figure IV.16. Correlation Plot for Normal Population, Wrist Range of Motion, Wrist Component
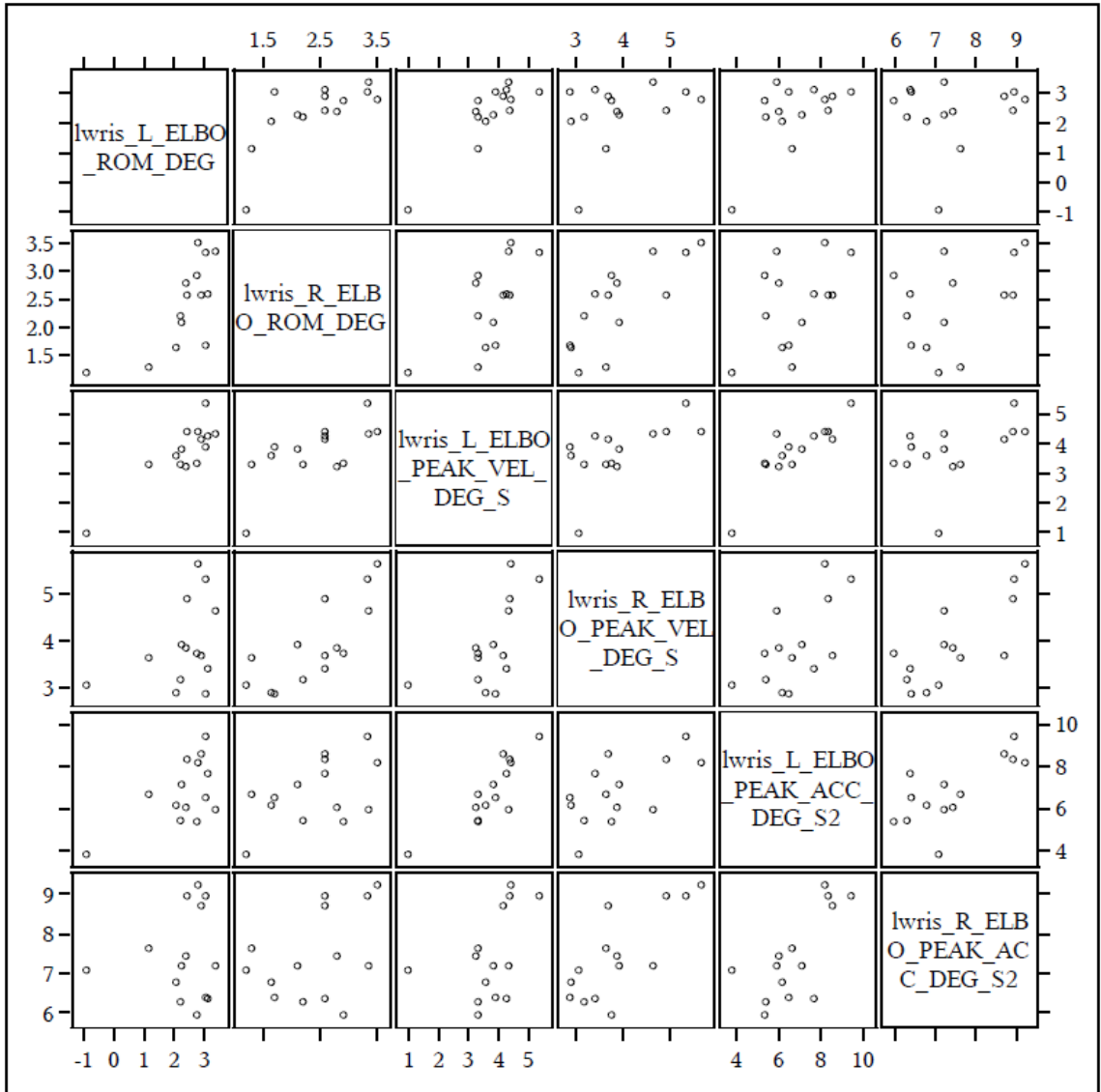
Figure IV.17. Correlation Plot for Normal Population, Wrist Range of Motion, Elbow Component
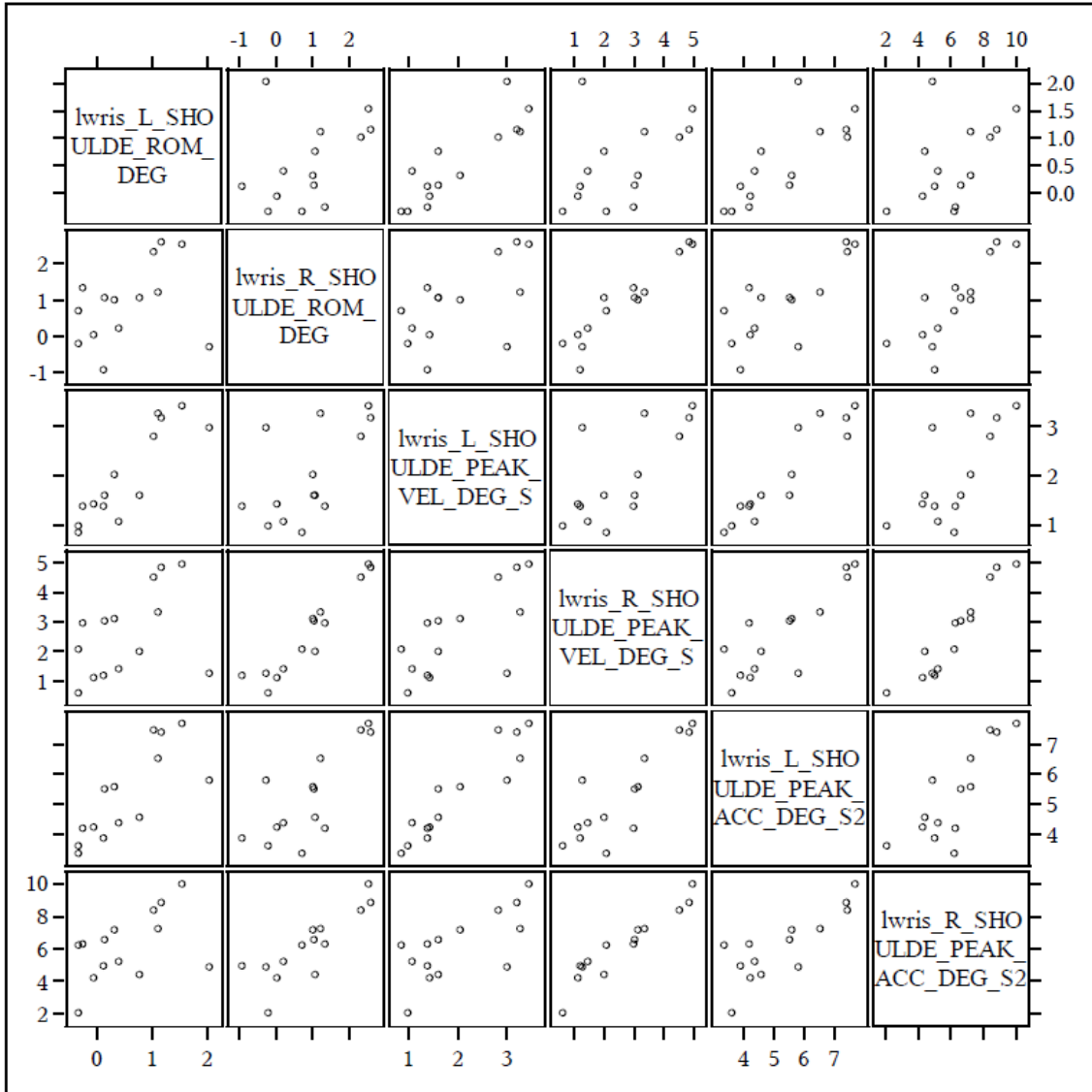
Figure IV.18. Correlation Plot for Normal Population, Wrist Range of Motion, Shoulder Component

ACTIVITY 6: ELBOW RANGE OF MOTION
KINEMATIC FOCUS: Elbow flexion/extension
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: Instruct subject to hold both arms outward at sides, with palms facing upward, and flex and extend the elbow to the extent possible in a repeating pattern. Repeat for 10-20+ cycles and ensure both arms are tracked fully by the software throughout.

0%   25%   50%   75%   100%
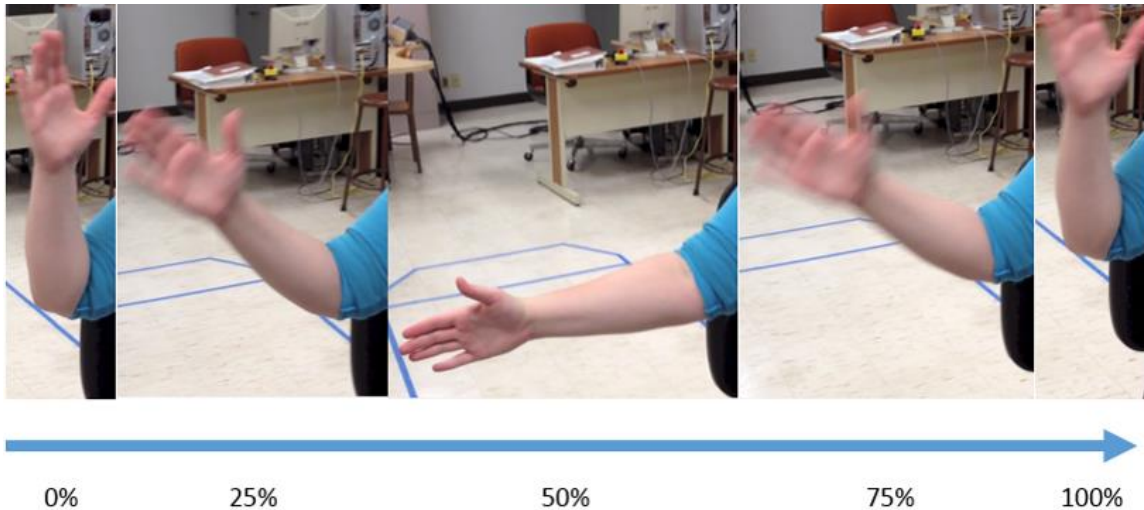
Figure IV.19. Activity Timeline for Elbow Range of Motion

Table IV.19. Kinect-detected Parameters for Exemplar Subject, Elbow Range of Motion

Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	15.475°	Right Wrist ROM	6.620°
Left Wrist Peak Velocity	116.509°/s	Right Wrist Peak Velocity	26.427°/s
Left Wrist Peak Acceleration	1493.800°/s^2	Right Wrist Peak Acceleration	307.530°/s^2
Left Elbow ROM	130.857°	Right Elbow ROM	123.897°
Left Elbow Peak Velocity	253.791°/s	Right Elbow Peak Velocity	284.390°/s
Left Elbow Peak Acceleration	1149.110°/s^2	Right Elbow Peak Acceleration	1249.661°/s^2
Left Shoulder ROM	10.755°	Right Shoulder ROM	17.434°
Left Shoulder Peak Velocity	32.856°/s	Right Shoulder Peak Velocity	57.431°/s
Left Shoulder Peak Acceleration	305.786°/s^2	Right Shoulder Peak Acceleration	507.378°/s^2
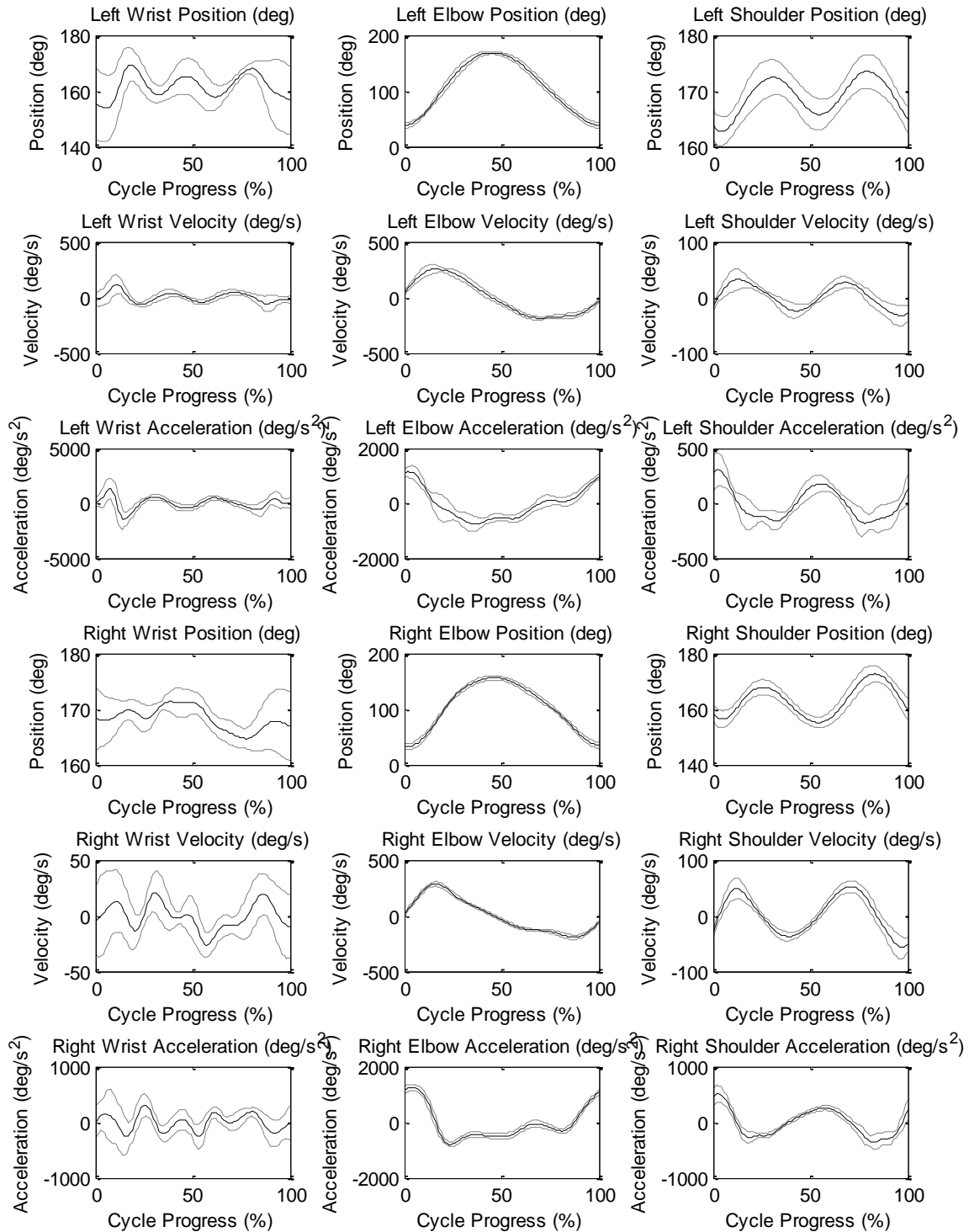
Figure IV.20. Kinematic Plots for Exemplar Subject, Elbow Range of Motion

Table IV.20. Kinect Normal Population Statistics, Elbow Range of Motion

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	32.90°	11.24°	10.64°	47.27°
Left Wrist Peak Velocity	n=12	266.15°/s	122.73°/s	63.77°/s	524.83°/s
Left Wrist Peak Acceleration	n=12	13381°/s²	6117°/s²	2850°/s²	22455°/s²
Left Elbow ROM	n=12	121.46°	21.75°	74.65°	148.95°
Left Elbow Peak Velocity	n=12	292.76°/s	77.38°/s	182.21°/s	486.54°/s
Left Elbow Peak Acceleration	n=12	4581°/s²	3261°/s²	1397°/s²	14382°/s²
Left Shoulder ROM	n=12	12.35°	7.98°	3.21°	30.34°
Left Shoulder Peak Velocity	n=12	51.70°/s	29.63°/s	19.90°/s	120.88°/s
Left Shoulder Peak Acceleration	n=12	1415°/s²	1042°/s²	169.24°/s²	3924°/s²
Right Wrist ROM	n=12	24.92°	8.18°	7.87°	37.97°
Right Wrist Peak Velocity	n=12	185.59°/s	80.09°/s	59.84°/s	377.02°/s
Right Wrist Peak Acceleration	n=12	10180°/s²	4028°/s²	5759°/s²	17765°/s²
Right Elbow ROM	n=12	122.61°	17.54°	92.87°	149.01°
Right Elbow Peak Velocity	n=12	278.17°/s	53.69°/s	183.80°/s	385.98°/s
Right Elbow Peak Acceleration	n=12	3961°/s²	2307°/s²	1546°/s²	9387°/s²
Right Shoulder ROM	n=12	12.16°	3.95°	6.97°	18.22°
Right Shoulder Peak Velocity	n=12	64.06°/s	33.17°/s	22.91°/s	159.95°/s
Right Shoulder Peak Acceleration	n=12	1689°/s²	1322°/s²	217.72°/s²	4786°/s²

Table IV.21. Correlation Statistics, Elbow ROM – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.04176	1.00000				
Left Wrist Peak Velocity	0.78022	0.28791	1.00000			
Right Wrist Peak Velocity	0.19560	0.78901	0.31868	1.00000		
Left Wrist Peak Acceleration	0.48571	0.05055	0.63077	0.01099	1.00000	
Right Wrist Peak Acceleration	-0.05495	0.52527	0.07692	0.81538	-0.37143	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.22. Correlation Statistics, Elbow ROM – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	0.93846	1.00000				
Left Elbow Peak Velocity	0.18242	0.21758	1.00000			
Right Elbow Peak Velocity	0.18681	0.17363	0.51648	1.00000		
Left Elbow Peak Acceleration	-0.25714	-0.17802	0.60879	0.31868	1.00000	
Right Elbow Peak Acceleration	-0.15165	-0.11209	0.74066	0.65714	0.69670	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.23. Correlation Statistics, Elbow ROM – Shoulder Component

Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	0.28352	1.00000				
Left Shoulder Peak Velocity	0.81099	0.02418	1.00000			
Right Shoulder Peak Velocity	0.29231	0.56484	0.43736	1.00000		
Left Shoulder Peak Acceleration	0.20879	-0.00659	0.52527	0.38022	1.00000	
Right Shoulder Peak Acceleration	0.12527	0.14286	0.34066	0.71429	0.47692	1.00000

n=12; data converted to logarithmic scale prior to analysis
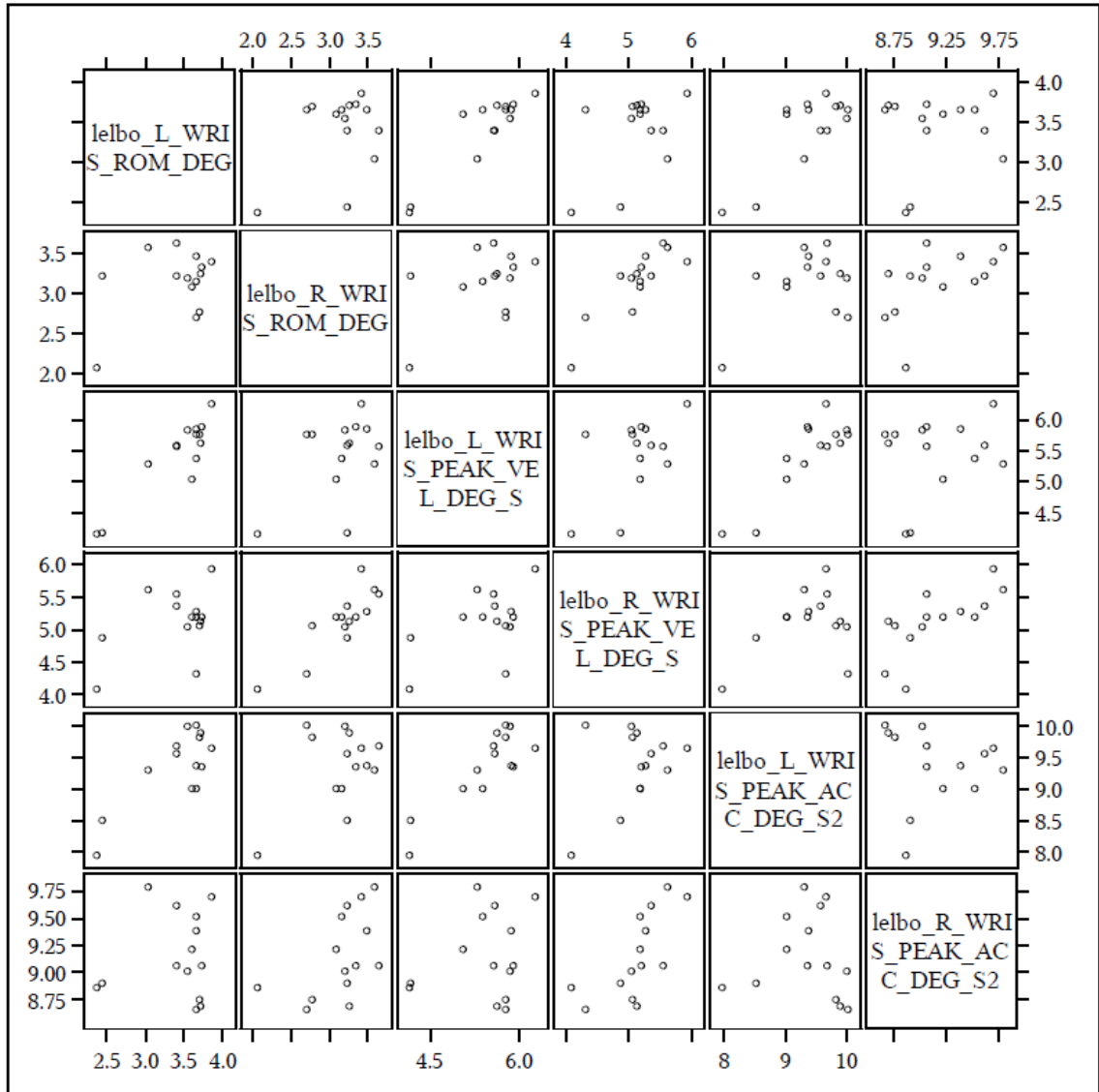
Figure IV.21. Correlation Plot for Normal Population, Elbow Range of Motion, Wrist Component
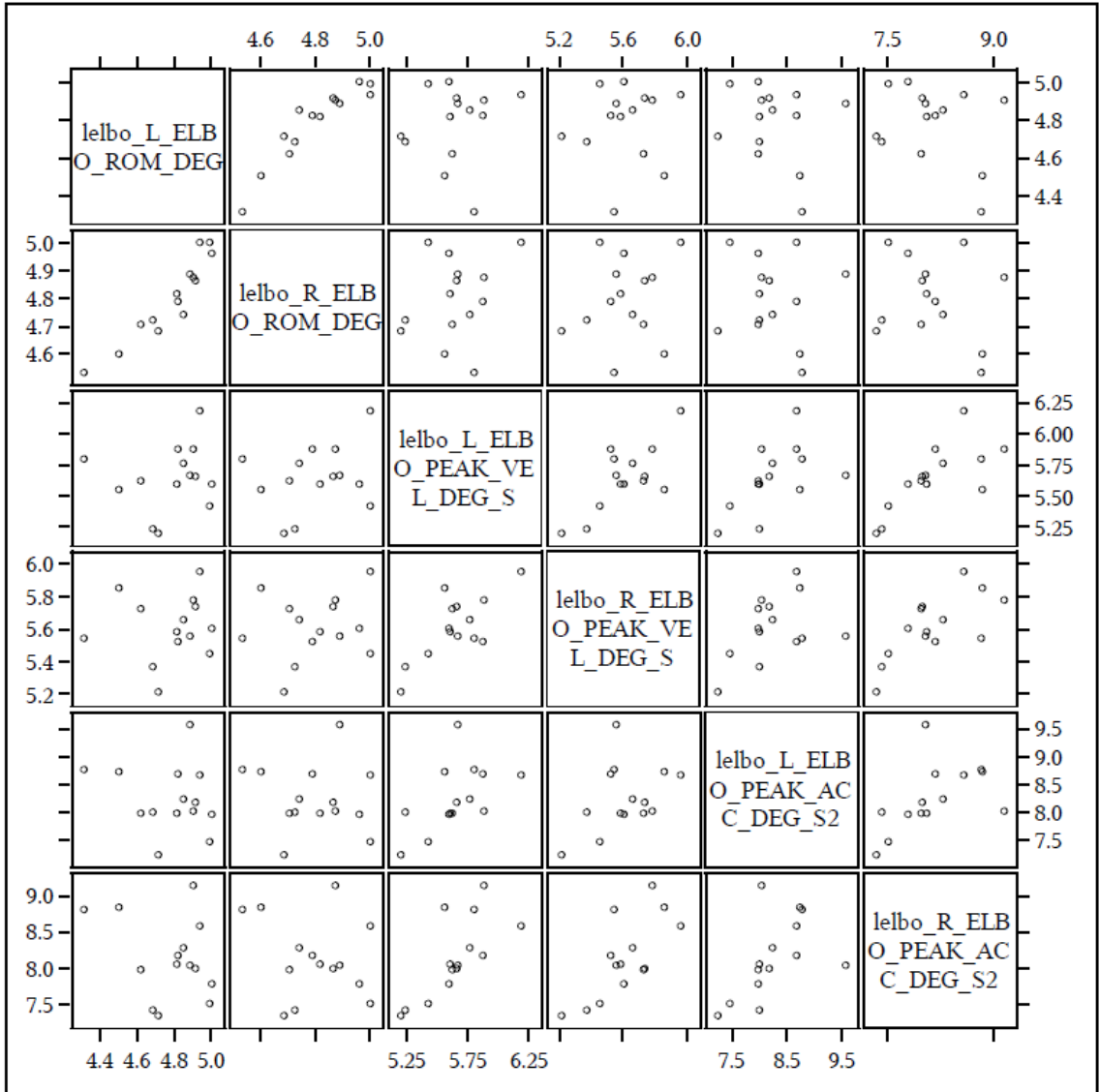
Figure IV.22. Correlation Plot for Normal Population, Elbow Range of Motion, Elbow Component
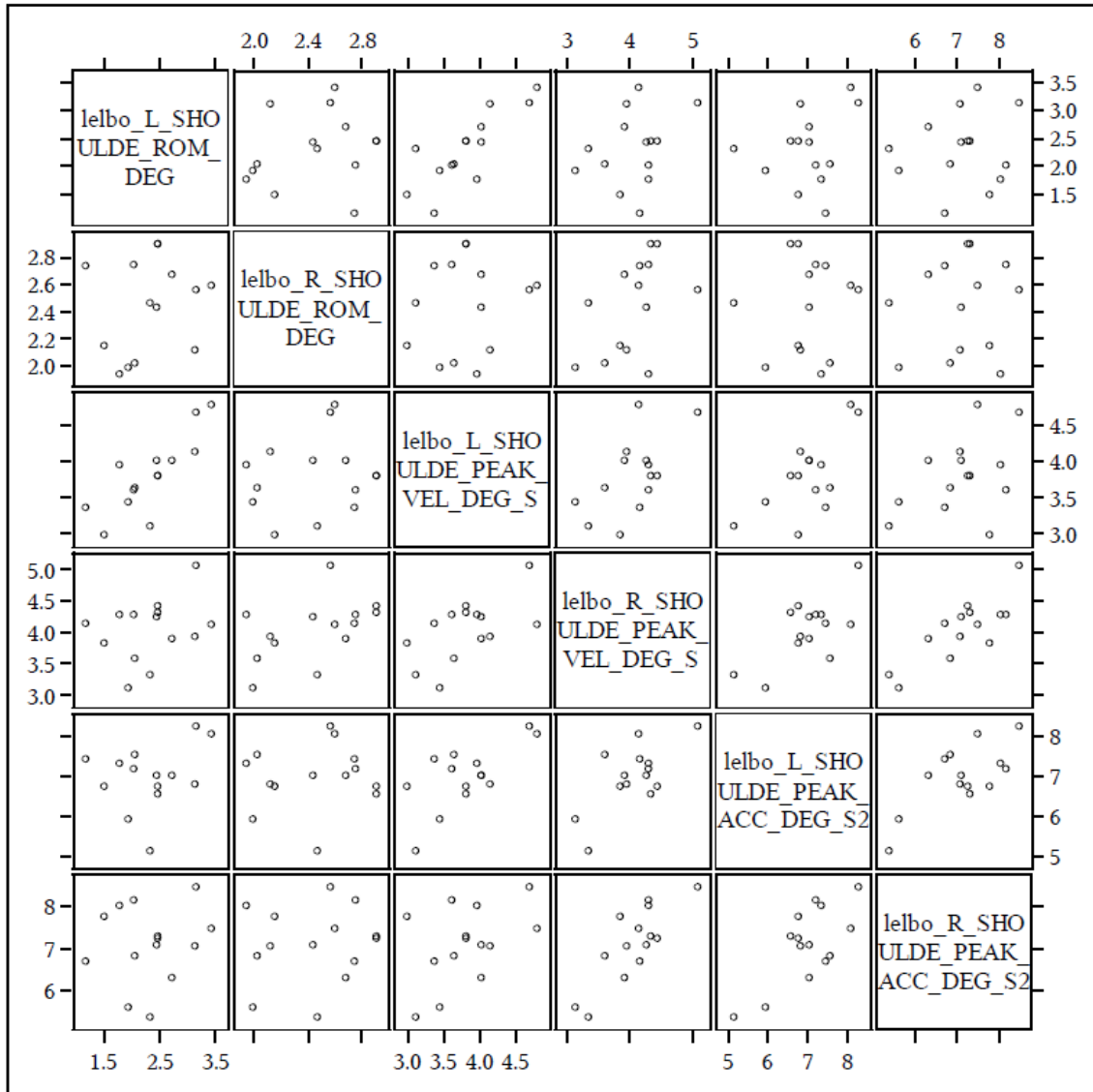
Figure IV.23. Correlation Plot for Normal Population, Elbow Range of Motion, Shoulder Component

ACTIVITY 7: SHOULDER RANGE OF MOTION
KINEMATIC FOCUS: Shoulder abduction/adduction
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: Instruct subject to hold both arms close to the body at sides, and raise and lower the arm, articulating at the shoulder, to the extent possible in a repeating pattern. Repeat for 10-20+ cycles and ensure both arms are tracked fully by the software throughout.
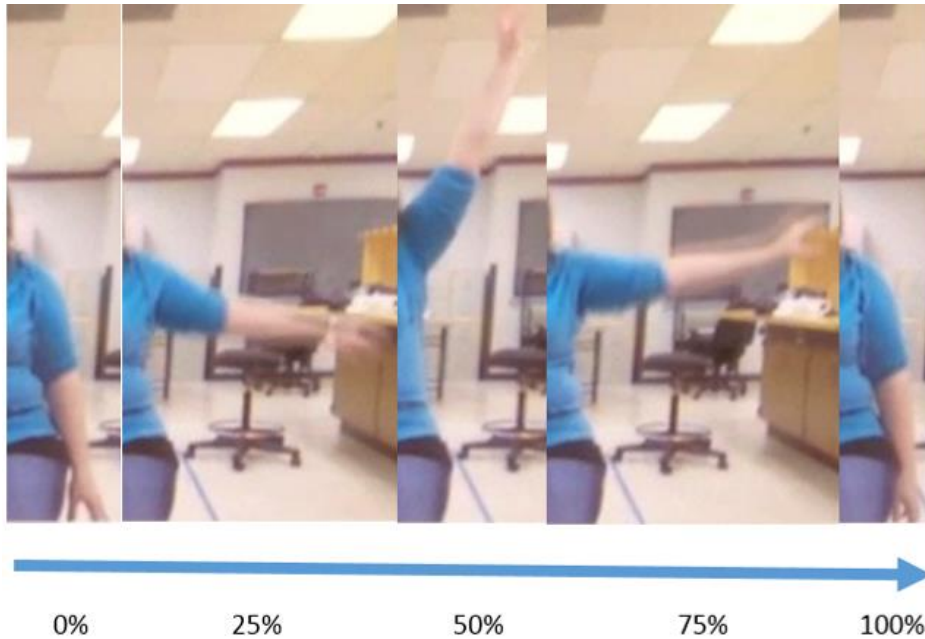
Figure IV.24. Activity Timeline for Shoulder Range of Motion

Table IV.24. Kinect-detected Parameters for Exemplar Subject, Shoulder Range of Motion

Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	9.203°	Right Wrist ROM	8.641°
Left Wrist Peak Velocity	37.352°/s	Right Wrist Peak Velocity	35.022°/s
Left Wrist Peak Acceleration	449.217°/s^2	Right Wrist Peak Acceleration	520.654°/s^2
Left Elbow ROM	7.776°	Right Elbow ROM	14.893°
Left Elbow Peak Velocity	37.791°/s	Right Elbow Peak Velocity	49.717°/s
Left Elbow Peak Acceleration	452.809°/s^2	Right Elbow Peak Acceleration	358.615°/s^2
Left Shoulder ROM	77.068°	Right Shoulder ROM	61.176°
Left Shoulder Peak Velocity	188.533°/s	Right Shoulder Peak Velocity	164.194°/s
Left Shoulder Peak Acceleration	4675.854°/s^2	Right Shoulder Peak Acceleration	3922.564°/s^2
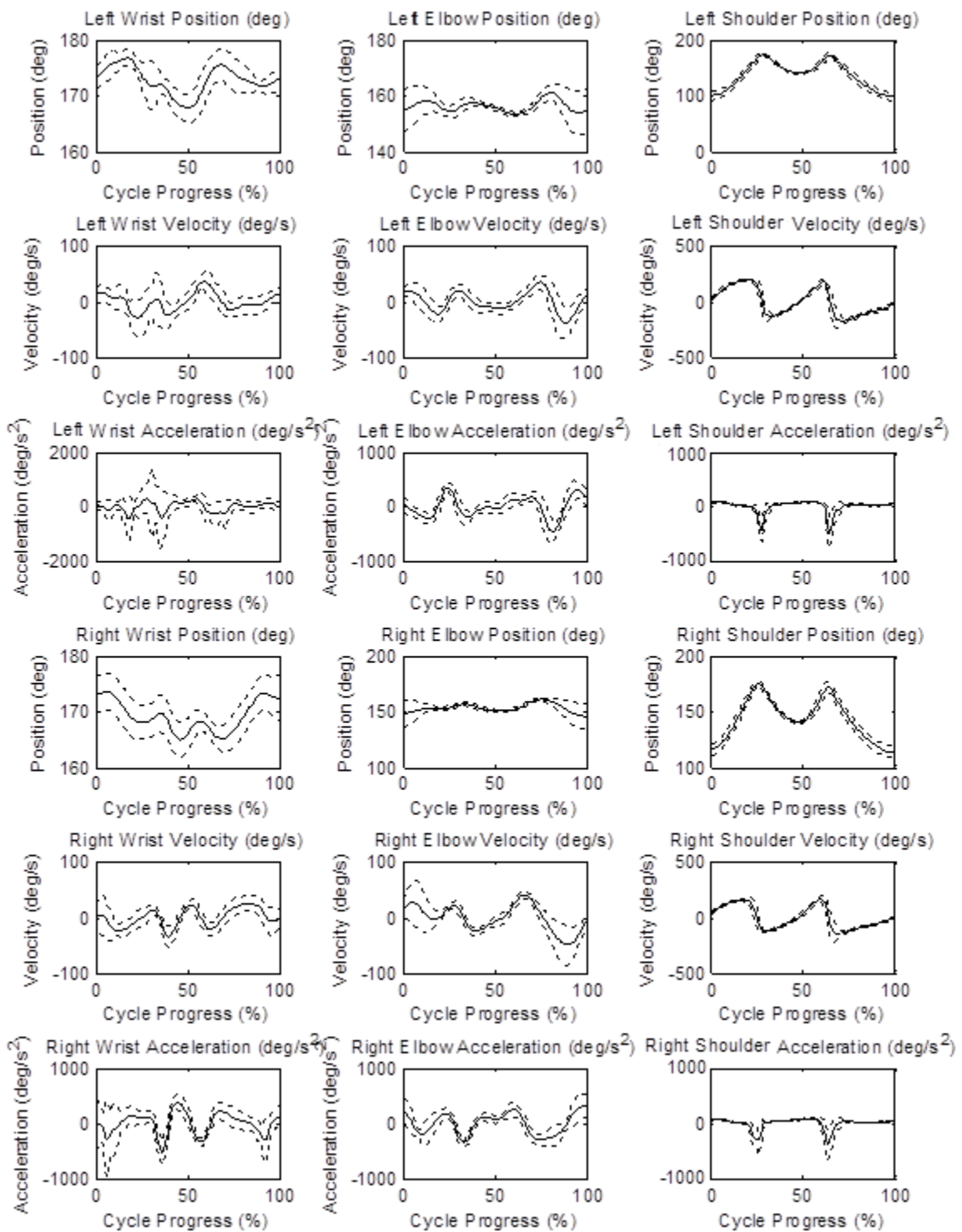
Figure IV.25. Kinematic Plots for Exemplar Subject, Shoulder Range of Motion

Table IV.25. Kinect Normal Population Statistics, Shoulder Range of Motion

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	29.30°	13.02°	9.88°	54.17°
Left Wrist Peak Velocity	n=12	274.34°/s	135.66°/s	79.82°/s	594.04°/s
Left Wrist Peak Acceleration	n=12	16503°/s^2	8187°/s^2	6673°/s^2	31600°/s^2
Left Elbow ROM	n=12	24.99°	13.77°	10.38°	53.37°
Left Elbow Peak Velocity	n=12	166.47°/s	103.84°/s	44.45°/s	385.98°/s
Left Elbow Peak Acceleration	n=12	6181°/s^2	4135°/s^2	2268°/s^2	15786°/s^2
Left Shoulder ROM	n=12	77.61°	14.41°	48.65°	100.69°
Left Shoulder Peak Velocity	n=12	219.65°/s	60.02°/s	142.26°/s	327.03°/s
Left Shoulder Peak Acceleration	n=12	5111°/s^2	2450°/s^2	1823°/s^2	9861°/s^2
Right Wrist ROM	n=12	30.40°	16.54°	9.99°	65.65°
Right Wrist Peak Velocity	n=12	231.97°/s	101.27°/s	88.71°/s	421.94°/s
Right Wrist Peak Acceleration	n=12	11630°/s^2	5809°/s^2	3290°/s^2	21346°/s^2
Right Elbow ROM	n=12	29.21°	14.48°	13.56°	57.63°
Right Elbow Peak Velocity	n=12	150.26°/s	111.36°/s	58.52°/s	457.49°/s
Right Elbow Peak Acceleration	n=12	5960°/s^2	6282°/s^2	2049°/s^2	20959°/s^2
Right Shoulder ROM	n=12	74.18°	16.69°	49.50°	98.41°
Right Shoulder Peak Velocity	n=12	211.62°/s	63.58°/s	130.56°/s	352.23°/s
Right Shoulder Peak Acceleration	n=12	5111°/s^2	3036°/s^2	1719°/s^2	11196°/s^2

Table IV.26. Correlation Statistics, Shoulder ROM – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.29670	1.00000				
Left Wrist Peak Velocity	0.86374	0.40220	1.00000			
Right Wrist Peak Velocity	0.18242	0.90769	0.26154	1.00000		
Left Wrist Peak Acceleration	0.68352	0.49451	0.85495	0.50769	1.00000	
Right Wrist Peak Acceleration	0.49451	0.58242	0.55165	0.55165	0.69670	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.27. Correlation Statistics, Shoulder ROM – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	0.86813	1.00000				
Left Elbow Peak Velocity	0.68791	0.62198	1.00000			
Right Elbow Peak Velocity	0.84176	0.84615	0.84176	1.00000		
Left Elbow Peak Acceleration	0.63077	0.56484	0.91648	0.85495	1.00000	
Right Elbow Peak Acceleration	0.45055	0.45495	0.72747	0.69670	0.73187	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.28. Correlation Statistics, Shoulder ROM – Shoulder Component

Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	0.80220	1.00000				
Left Shoulder Peak Velocity	0.56484	0.36264	1.00000			
Right Shoulder Peak Velocity	0.56044	0.76703	0.39341	1.00000		
Left Shoulder Peak Acceleration	0.45055	0.63516	0.40220	0.37582	1.00000	
Right Shoulder Peak Acceleration	0.46813	0.65714	0.32308	0.79341	0.52527	1.00000

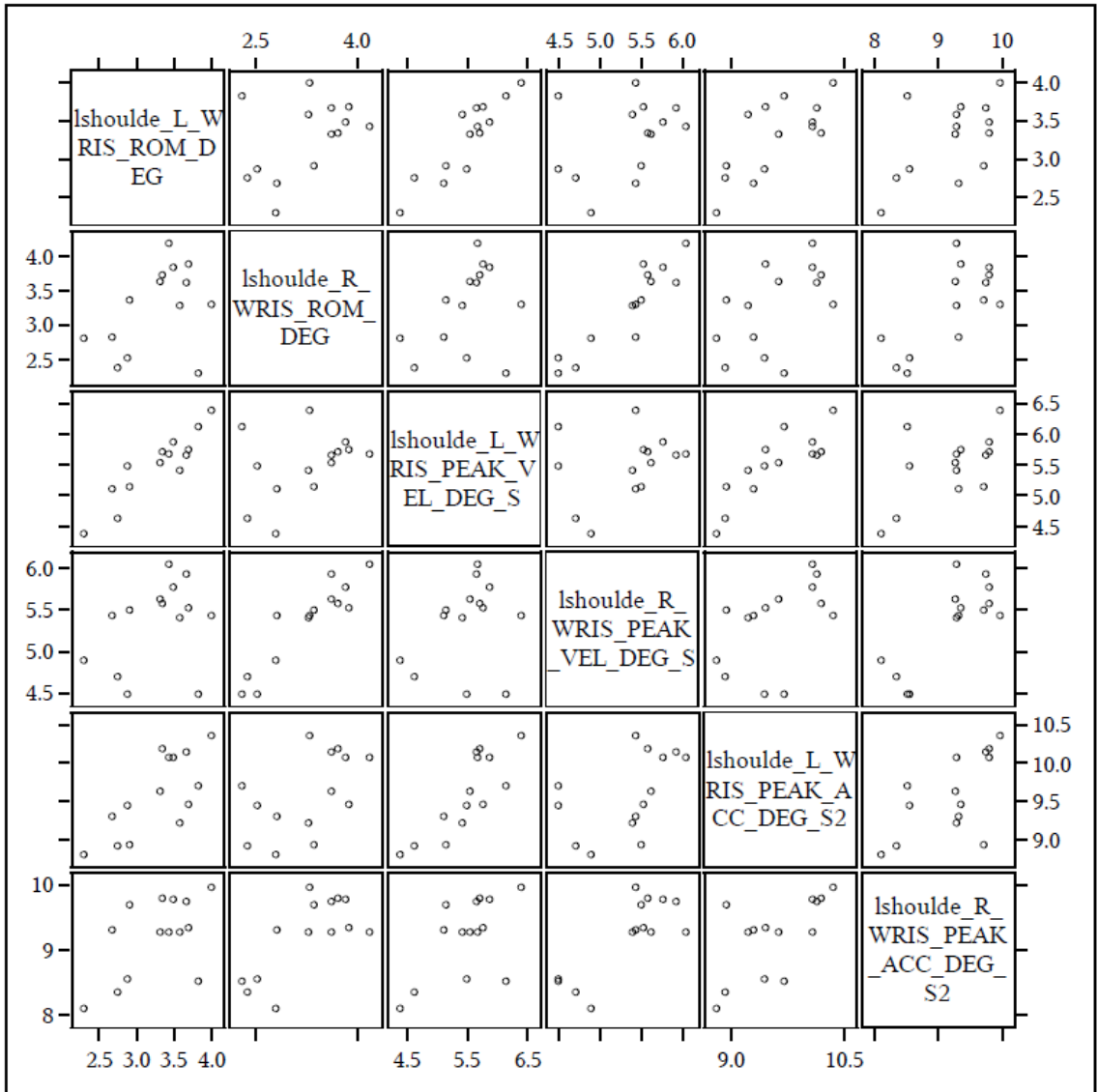n=12; data converted to logarithmic scale prior to analysis

Figure IV.26. Correlation Plot for Normal Population, Shoulder Range of Motion, Wrist Component
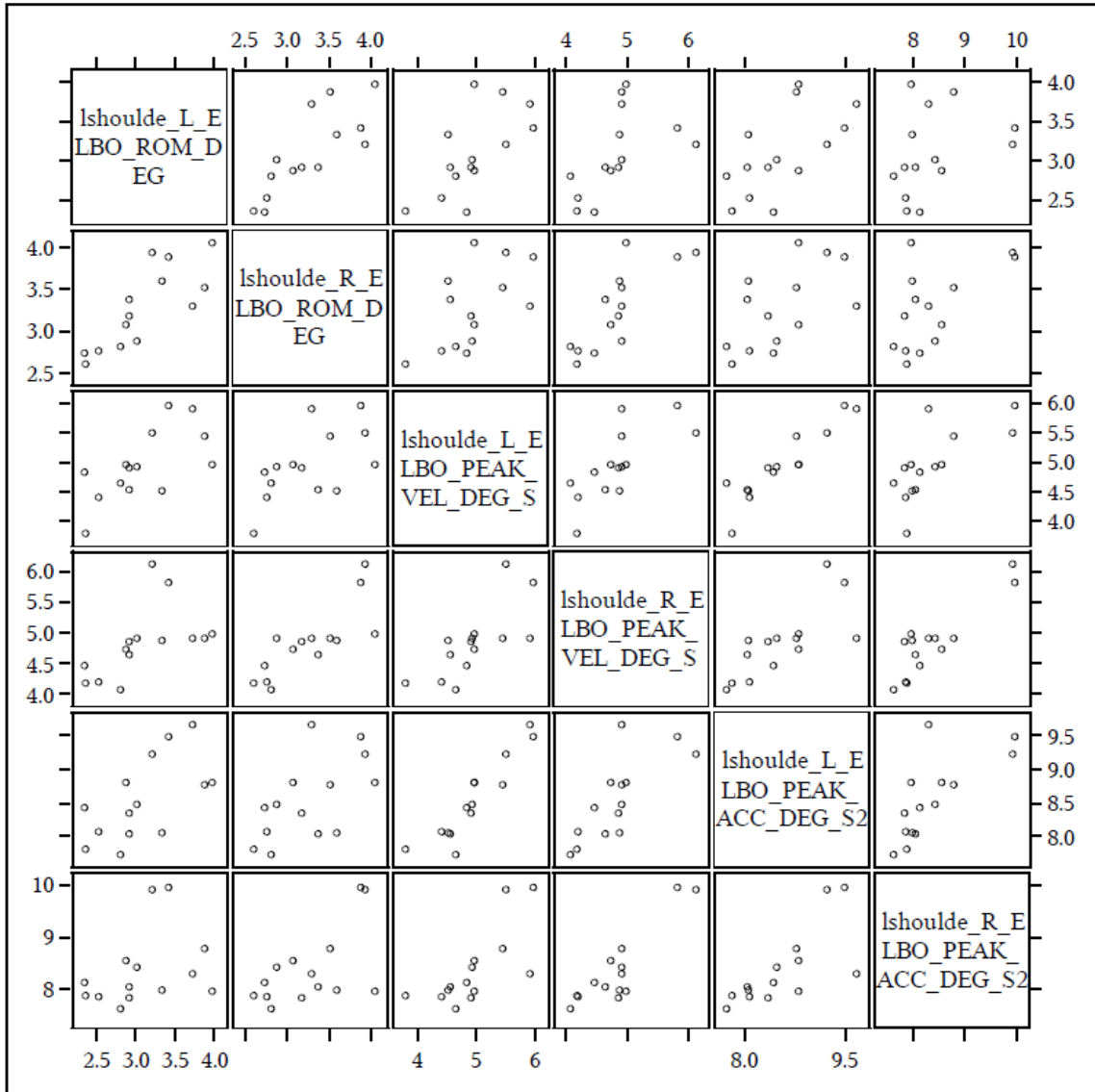
Figure IV.27. Correlation Plot for Normal Population, Shoulder Range of Motion, Elbow Component
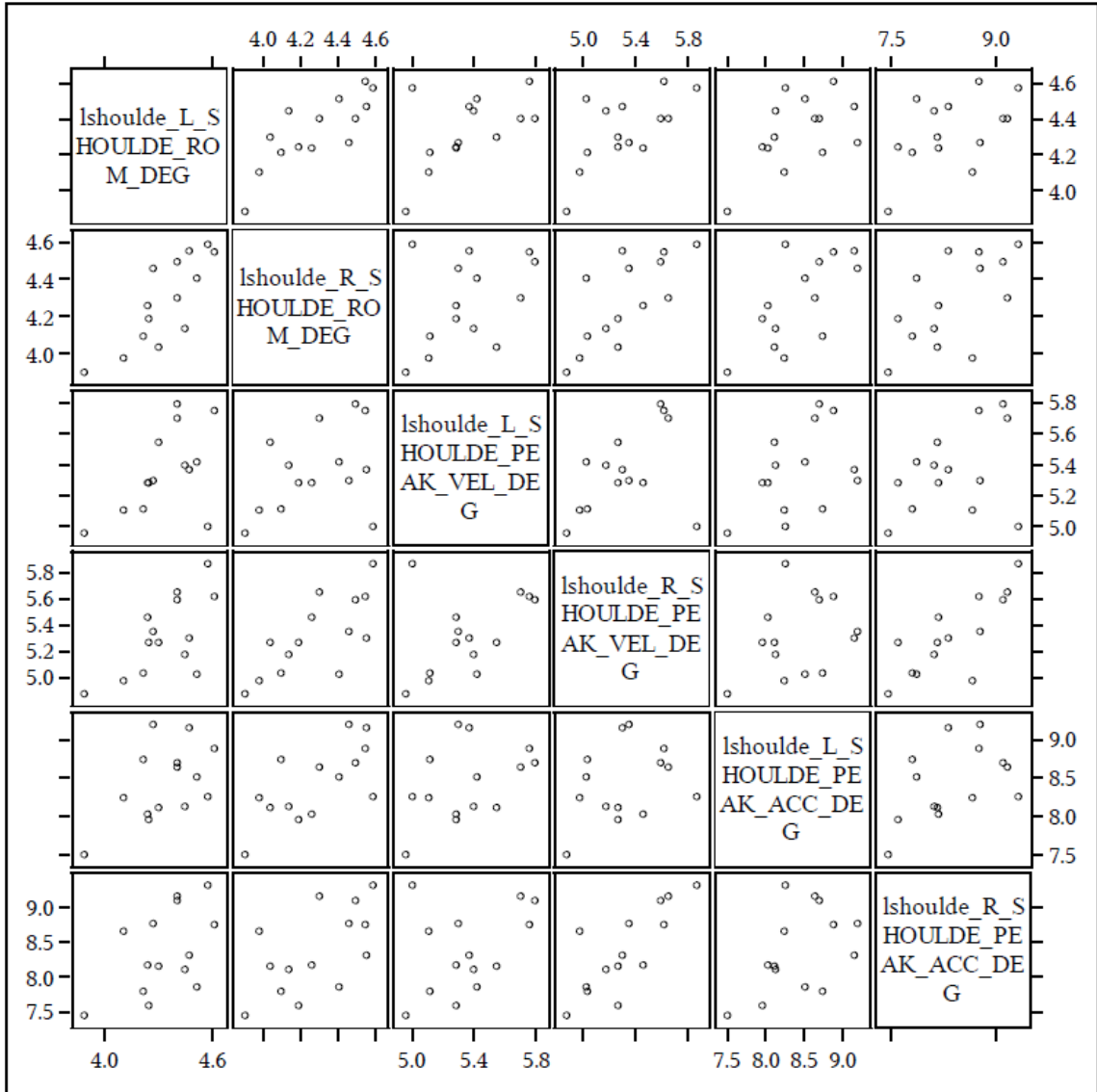
Figure IV.28. Correlation Plot for Normal Population, Shoulder Range of Motion, Shoulder Component

ACTIVITY 8: UNSCREW BOTTLE OR JAR CAP
KINEMATIC FOCUS: Wrist flexion/extension and radial/ulnar deviation
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: Instruct subject to hold jar with non-dominant hand and unscrew lid, in a repeating cyclic pattern, with dominant hand, repeating for 10-20+ cycles and ensuring that both arms are tracked fully throughout (the subject may need to hold the jar out in front of body to ensure accurate tracking).

0%   25%   50%   75%   100%
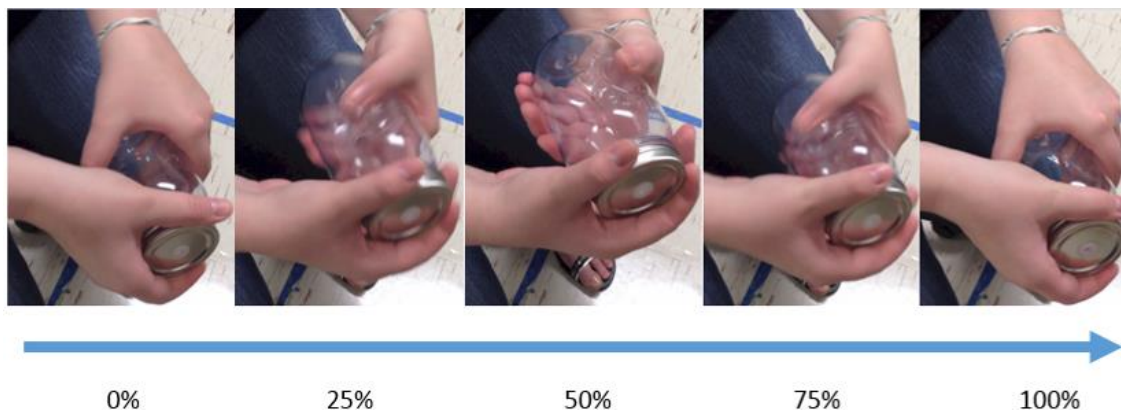
Figure IV.29. Activity Timeline for Unscrew Bottle Cap

Table IV.29. Kinect-detected Parameters for Exemplar Subject, Unscrew Bottle Cap

Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	15.971°	Right Wrist ROM	38.733°
Left Wrist Peak Velocity	57.539°/s	Right Wrist Peak Velocity	191.930°/s
Left Wrist Peak Acceleration	812.318°/s^2	Right Wrist Peak Acceleration	1987.489°/s^2
Left Elbow ROM	6.612°	Right Elbow ROM	7.409°
Left Elbow Peak Velocity	23.759°/s	Right Elbow Peak Velocity	21.756°/s
Left Elbow Peak Acceleration	260.916°/s^2	Right Elbow Peak Acceleration	163.332°/s^2
Left Shoulder ROM	7.372°	Right Shoulder ROM	4.214°
Left Shoulder Peak Velocity	29.487°/s	Right Shoulder Peak Velocity	14.465°/s
Left Shoulder Peak Acceleration	223.088°/s^2	Right Shoulder Peak Acceleration	102.000°/s^2
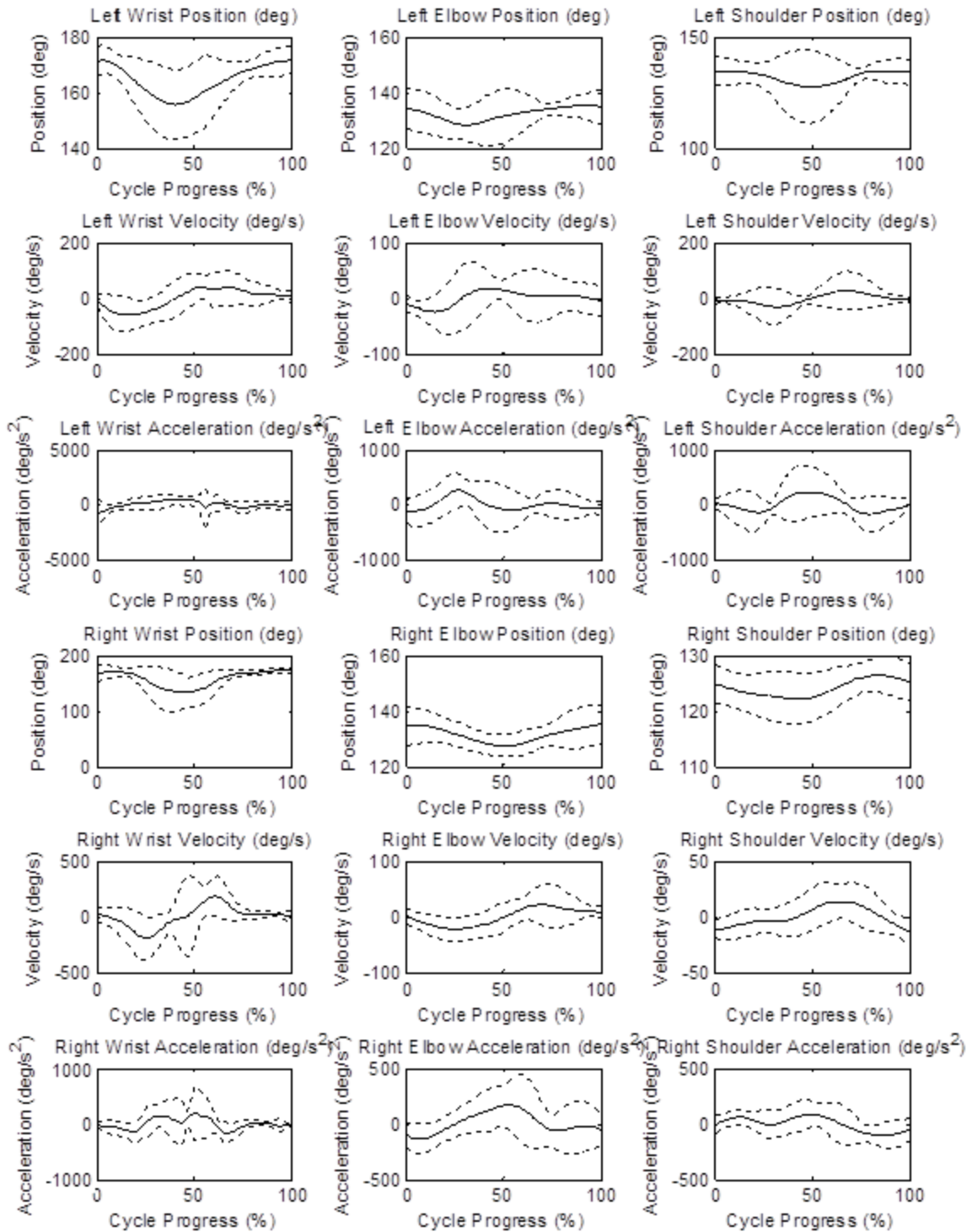
Figure IV.30. Kinematic Plots for Exemplar Subject, Unscrew Bottle Cap

Table IV.30. Kinect Normal Population Statistics, Unscrew Bottle Cap

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	36.15°	14.56°	16.06°	63.15°
Left Wrist Peak Velocity	n=12	340.74°/s	172.35°/s	145.51°/s	734.87°/s
Left Wrist Peak Acceleration	n=12	18960°/s²	11994°/s²	7584°/s²	51438°/s²
Left Elbow ROM	n=12	21.00°	11.47°	9.54°	37.98°
Left Elbow Peak Velocity	n=12	166.04°/s	88.02°/s	55.07°/s	326.55°/s
Left Elbow Peak Acceleration	n=12	8762°/s²	5122°/s²	2511°/s²	21182°/s²
Left Shoulder ROM	n=12	13.42°	11.35°	1.53°	34.80°
Left Shoulder Peak Velocity	n=12	89.70°/s	5.52°/s	5.24°/s	274.74°/s
Left Shoulder Peak Acceleration	n=12	4717°/s²	5332°/s²	120.21°/s²	20324°/s²
Right Wrist ROM	n=12	34.10°	8.33°	19.08°	50.89°
Right Wrist Peak Velocity	n=12	318.76°/s	122.16°/s	188.32°/s	616.94°/s
Right Wrist Peak Acceleration	n=12	18136°/s²	10152°/s²	9503°/s²	51289°/s²
Right Elbow ROM	n=12	17.87°	8.29°	9.54°	37.98°
Right Elbow Peak Velocity	n=12	127.61°/s	59.47°/s	67.89°/s	257.99°/s
Right Elbow Peak Acceleration	n=12	5915°/s²	2799°/s²	2580°/s²	10252°/s²
Right Shoulder ROM	n=12	9.45°	5.52°	1.85°	18.20°
Right Shoulder Peak Velocity	n=12	76.76°/s	47.55°/s	8.27°/s	187.04°/s
Right Shoulder Peak Acceleration	n=12	3446°/s²	2200°/s²	224.67°/s²	7478°/s²

Table IV.31. Correlation Statistics, Unscrew Bottle Cap – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.36703	1.00000				
Left Wrist Peak Velocity	0.91209	0.34945	1.00000			
Right Wrist Peak Velocity	0.48132	0.84615	0.55165	1.00000		
Left Wrist Peak Acceleration	0.69670	0.31429	0.79780	0.49890	1.00000	
Right Wrist Peak Acceleration	0.12967	0.81099	0.05495	0.50330	0.13846	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.32. Correlation Statistics, Unscrew Bottle Cap – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	0.21319	1.00000				
Left Elbow Peak Velocity	0.92967	0.30110	1.00000			
Right Elbow Peak Velocity	0.33187	0.78462	0.35385	1.00000		
Left Elbow Peak Acceleration	0.90330	0.33626	0.89011	0.35824	1.00000	
Right Elbow Peak Acceleration	0.55165	0.58681	0.56044	0.81099	0.52527	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.33. Correlation Statistics, Unscrew Bottle Cap – Shoulder Component

Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	0.10330	1.00000				
Left Shoulder Peak Velocity	0.98242	0.01978	1.00000			
Right Shoulder Peak Velocity	0.19560	0.91209	0.10769	1.00000		
Left Shoulder Peak Acceleration	0.92527	-0.04615	0.93407	0.07253	1.00000	
Right Shoulder Peak Acceleration	0.20440	0.82857	0.08132	0.89011	0.05934	1.00000

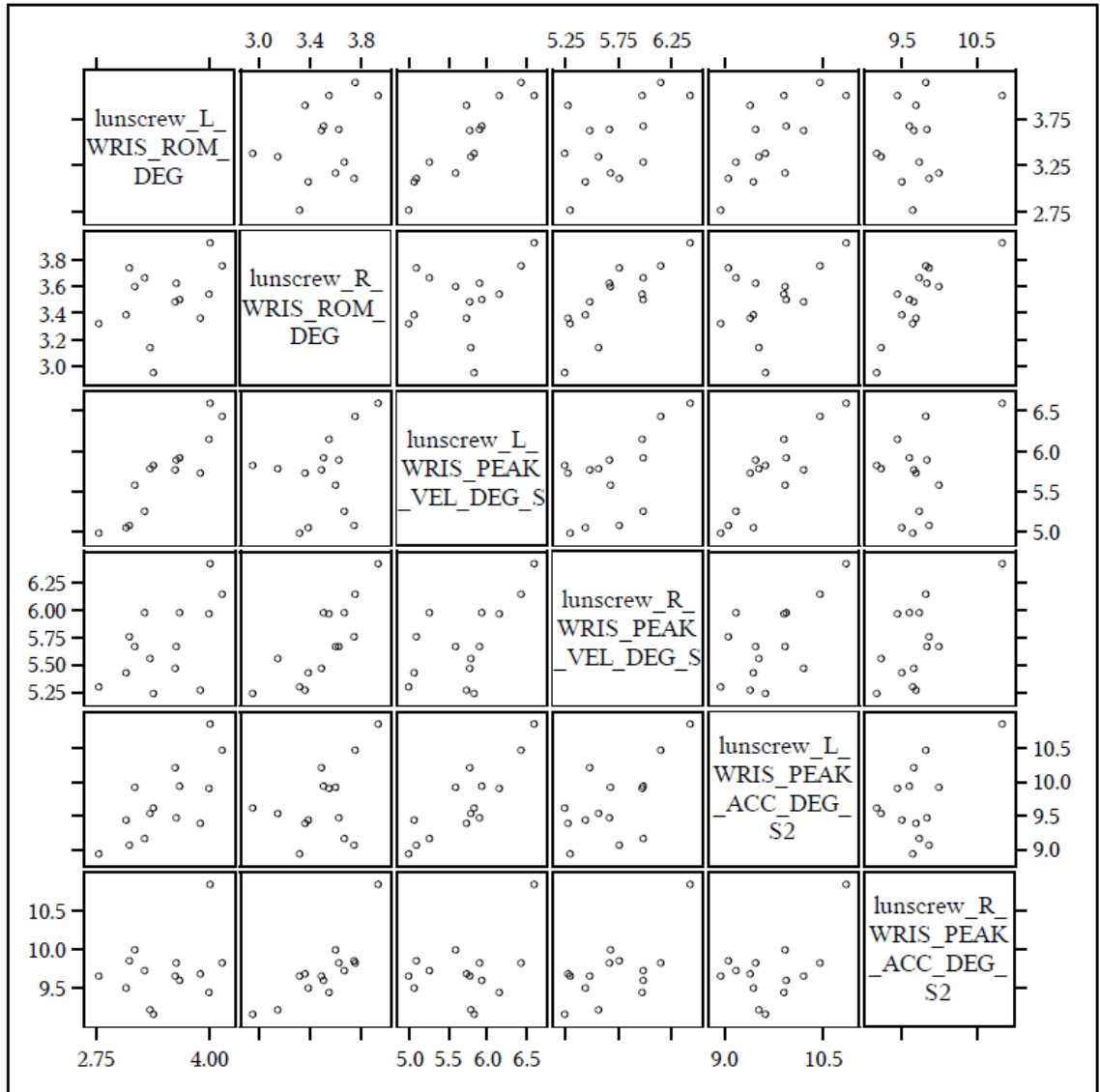n=12; data converted to logarithmic scale prior to analysis

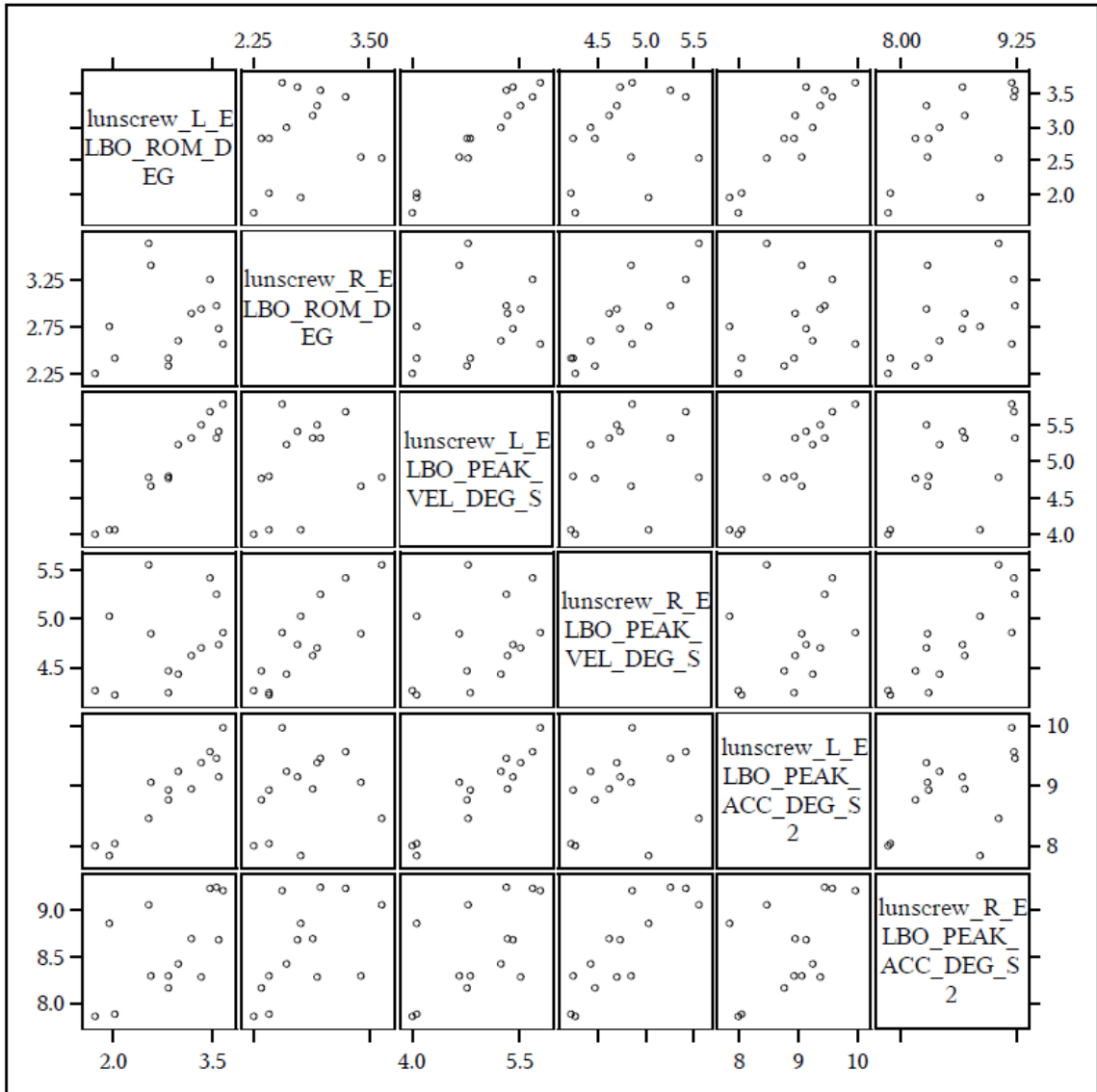*Figure IV.31.* Correlation Plot for Normal Population, Unscrew Bottle Cap, Wrist Component

Figure IV.32. Correlation Plot for Normal Population, Unscrew Bottle Cap, Elbow Component
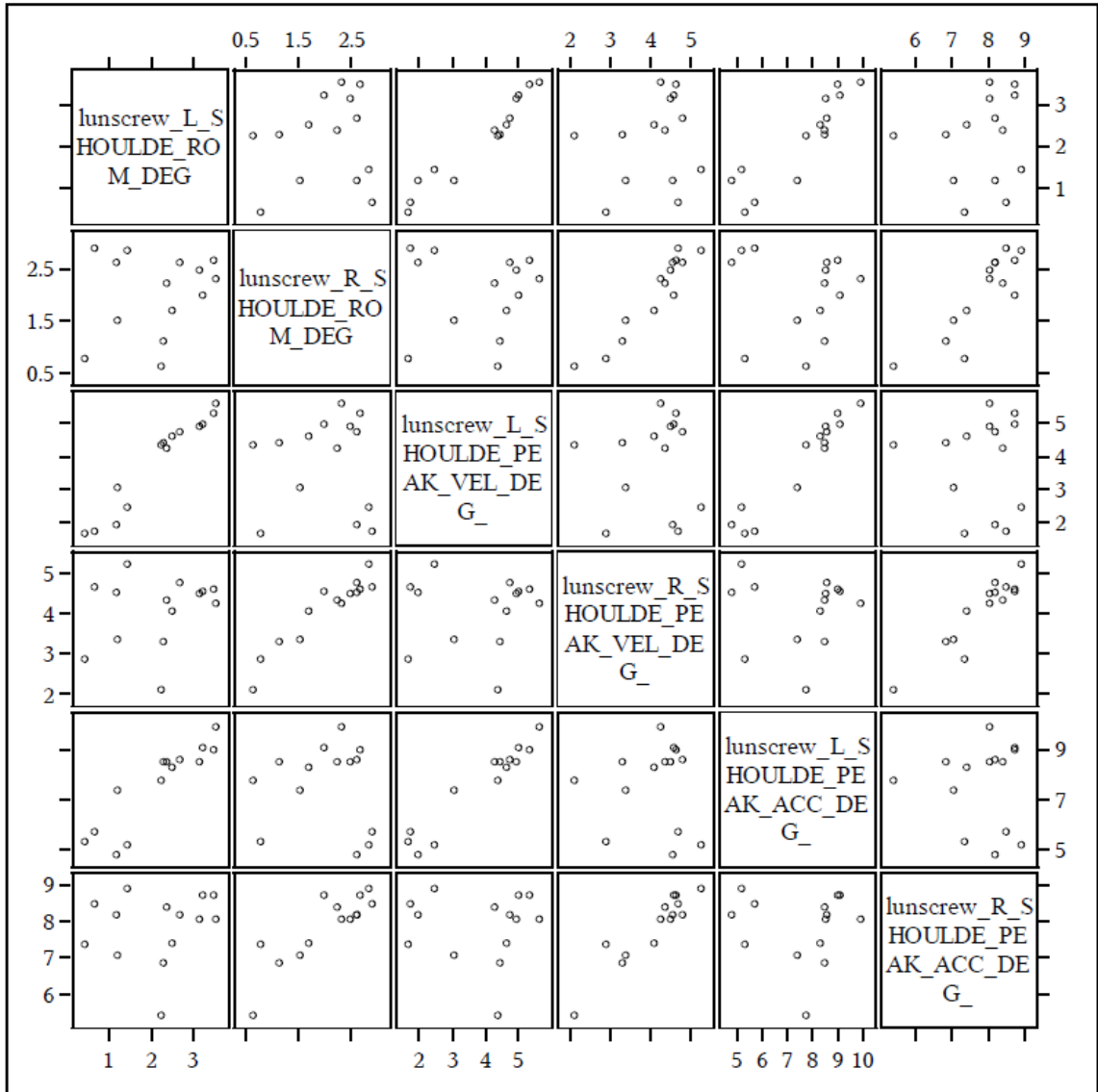
Figure IV.33. Correlation Plot for Normal Population, Unscrew Bottle Cap, Shoulder Component

ACTIVITY 9: PULL PLAY-DOH® APART
KINEMATIC FOCUS: Wrist flexion/extension and radial/ulnar deviation
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: Mold Play-Doh into cylindrical shape and ask subject to pull apart into multiple pieces, holding arms in front of body. Repeat for 10-20+ cycles ensuring that both arms are tracked throughout.
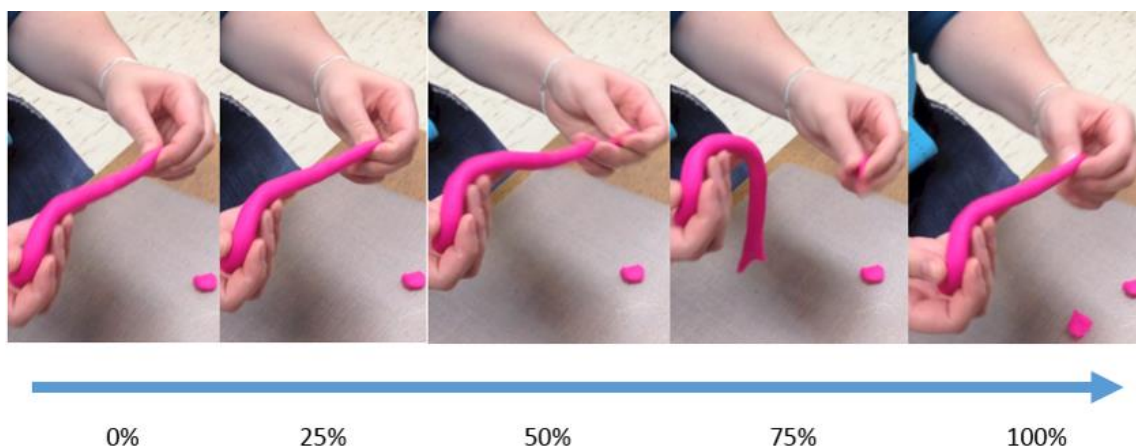
Figure IV.34. Activity Timeline for Pull Play-Doh Apart

Table IV.34. Kinect-detected Parameters for Exemplar Subject, Pull Play-Doh Apart

Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	8.139°	Right Wrist ROM	14.426°
Left Wrist Peak Velocity	45.090°/s	Right Wrist Peak Velocity	57.165°/s
Left Wrist Peak Acceleration	631.184°/s^2	Right Wrist Peak Acceleration	1180.577°/s^2
Left Elbow ROM	23.984°	Right Elbow ROM	14.938°
Left Elbow Peak Velocity	59.134°/s	Right Elbow Peak Velocity	42.945°/s
Left Elbow Peak Acceleration	324.732°/s^2	Right Elbow Peak Acceleration	195.998°/s^2
Left Shoulder ROM	14.587°	Right Shoulder ROM	10.415°
Left Shoulder Peak Velocity	32.711°/s	Right Shoulder Peak Velocity	26.390°/s
Left Shoulder Peak Acceleration	214.160°/s^2	Right Shoulder Peak Acceleration	147.053°/s^2
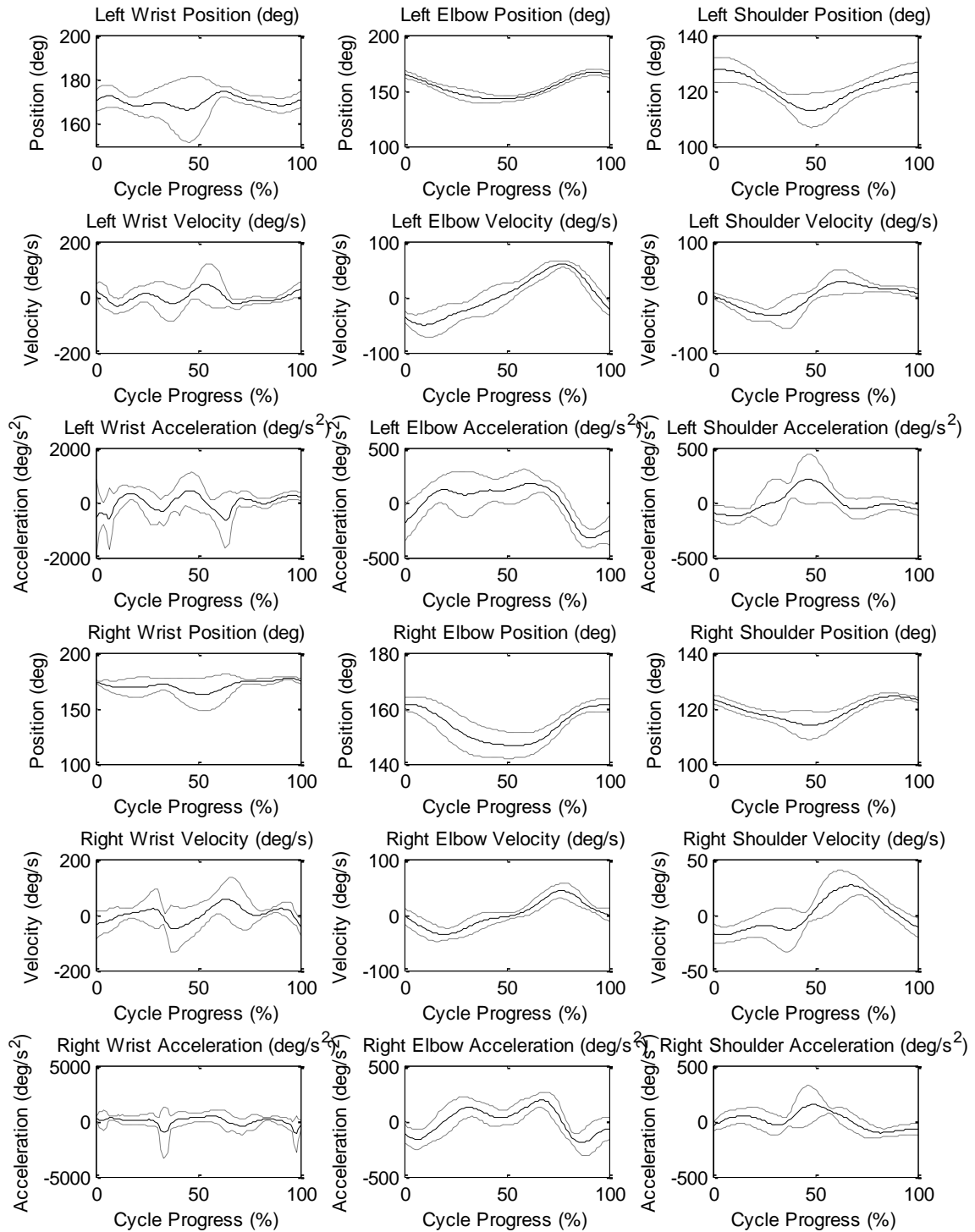
Figure IV.35. Kinematic Plots for Exemplar Subject, Pull Play-Doh Apart

Table IV.35. Kinect Normal Population Statistics, Pull Play-Doh Apart

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	29.35°	15.58°	11.32°	54.96°
Left Wrist Peak Velocity	n=12	242.12°/s	119.79°/s	87.01°/s	538.24°/s
Left Wrist Peak Acceleration	n=12	13111°/s²	8209°/s²	4511°/s²	37180°/s²
Left Elbow ROM	n=12	21.99°	9.80°	3.68°	36.89°
Left Elbow Peak Velocity	n=12	148.01°/s	86.38°/s	41.10°/s	306.90°/s
Left Elbow Peak Acceleration	n=12	6254°/s²	5137°/s²	846.33°/s²	16652°/s²
Left Shoulder ROM	n=12	16.76°	11.22°	1.04°	40.69°
Left Shoulder Peak Velocity	n=12	83.92°/s	54.68°/s	4.29°/s	198.98°/s
Left Shoulder Peak Acceleration	n=12	3136°/s²	2186°/s²	130.05°/s²	8261°/s²
Right Wrist ROM	n=12	38.18°	22.93°	11.99°	98.00°
Right Wrist Peak Velocity	n=12	327.49°/s	199.07°/s	95.43°/s	907.33°/s
Right Wrist Peak Acceleration	n=12	20220°/s²	16805°/s²	4068°/s²	64263°/s²
Right Elbow ROM	n=12	17.45°	8.54°	17.12°	6.80°
Right Elbow Peak Velocity	n=12	119.60°/s	76.62°/s	39.26°/s	297.66°/s
Right Elbow Peak Acceleration	n=12	5992°/s²	6870°/s²	1272°/s²	28144°/s²
Right Shoulder ROM	n=12	12.86°	9.71°	1.61°	42.13°
Right Shoulder Peak Velocity	n=12	77.73°/s	49.54°/s	11.68°/s	165.98°/s
Right Shoulder Peak Acceleration	n=12	3497°/s²	2930°/s²	423.23°/s²	10437°/s²

Table IV.36. Correlation Statistics, Pull Play-Doh® Apart – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.07253	1.00000				
Left Wrist Peak Velocity	0.88571	0.02418	1.00000			
Right Wrist Peak Velocity	-0.18681	0.81978	-0.22198	1.00000		
Left Wrist Peak Acceleration	0.72308	-0.29231	0.67033	-0.36264	1.00000	
Right Wrist Peak Acceleration	-0.30549	0.59121	-0.23516	0.91209	-0.29670	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.37. Correlation Statistics, Pull Play-Doh® Apart – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	0.56044	1.00000				
Left Elbow Peak Velocity	0.86813	0.67912	1.00000			
Right Elbow Peak Velocity	0.48132	0.82418	0.61319	1.00000		
Left Elbow Peak Acceleration	0.62637	0.60440	0.89011	0.58681	1.00000	
Right Elbow Peak Acceleration	0.45934	0.67033	0.61319	0.90330	0.67473	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.38. Correlation Statistics, Pull Play-Doh® Apart – Shoulder Component

Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	0.52967	1.00000				
Left Shoulder Peak Velocity	0.81099	0.62637	1.00000			
Right Shoulder Peak Velocity	0.70549	0.81538	0.90330	1.00000		
Left Shoulder Peak Acceleration	0.66154	0.59121	0.91648	0.92088	1.00000	
Right Shoulder Peak Acceleration	0.47253	0.52527	0.78022	0.79870	0.84176	1.00000

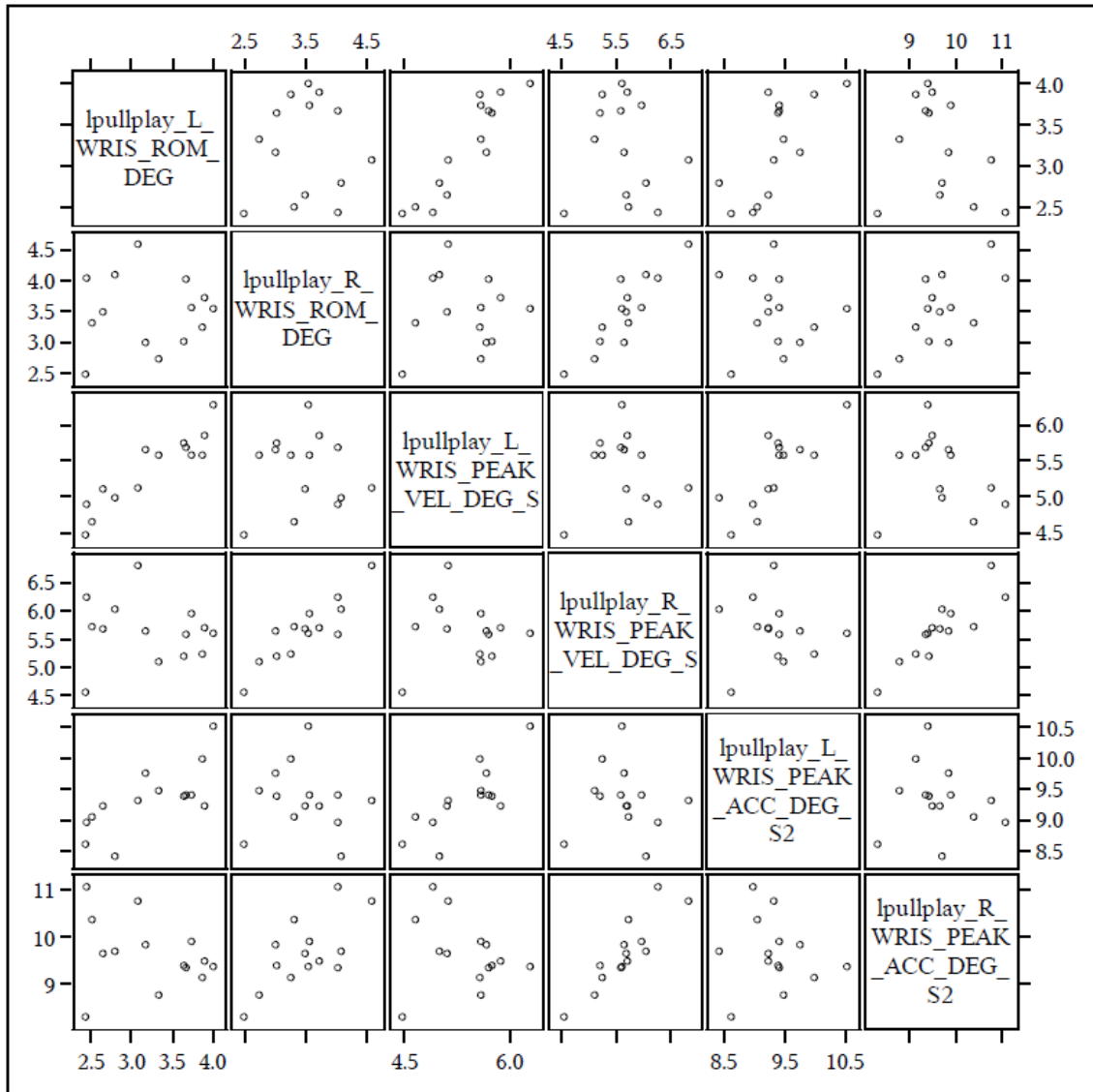n=12; data converted to logarithmic scale prior to analysis

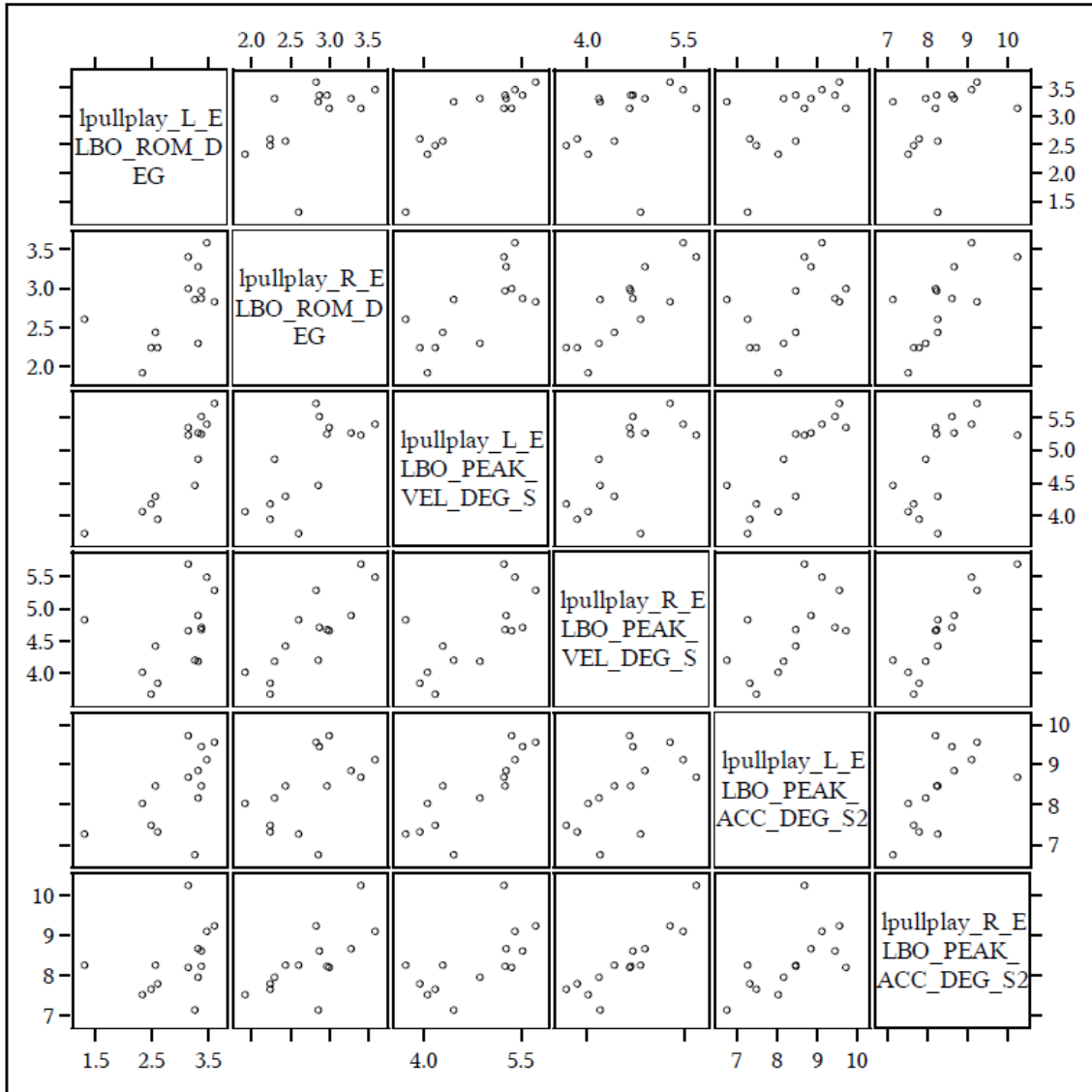*Figure IV.36.* Correlation Plot for Normal Population, Pull Play-Doh Apart, Wrist Component

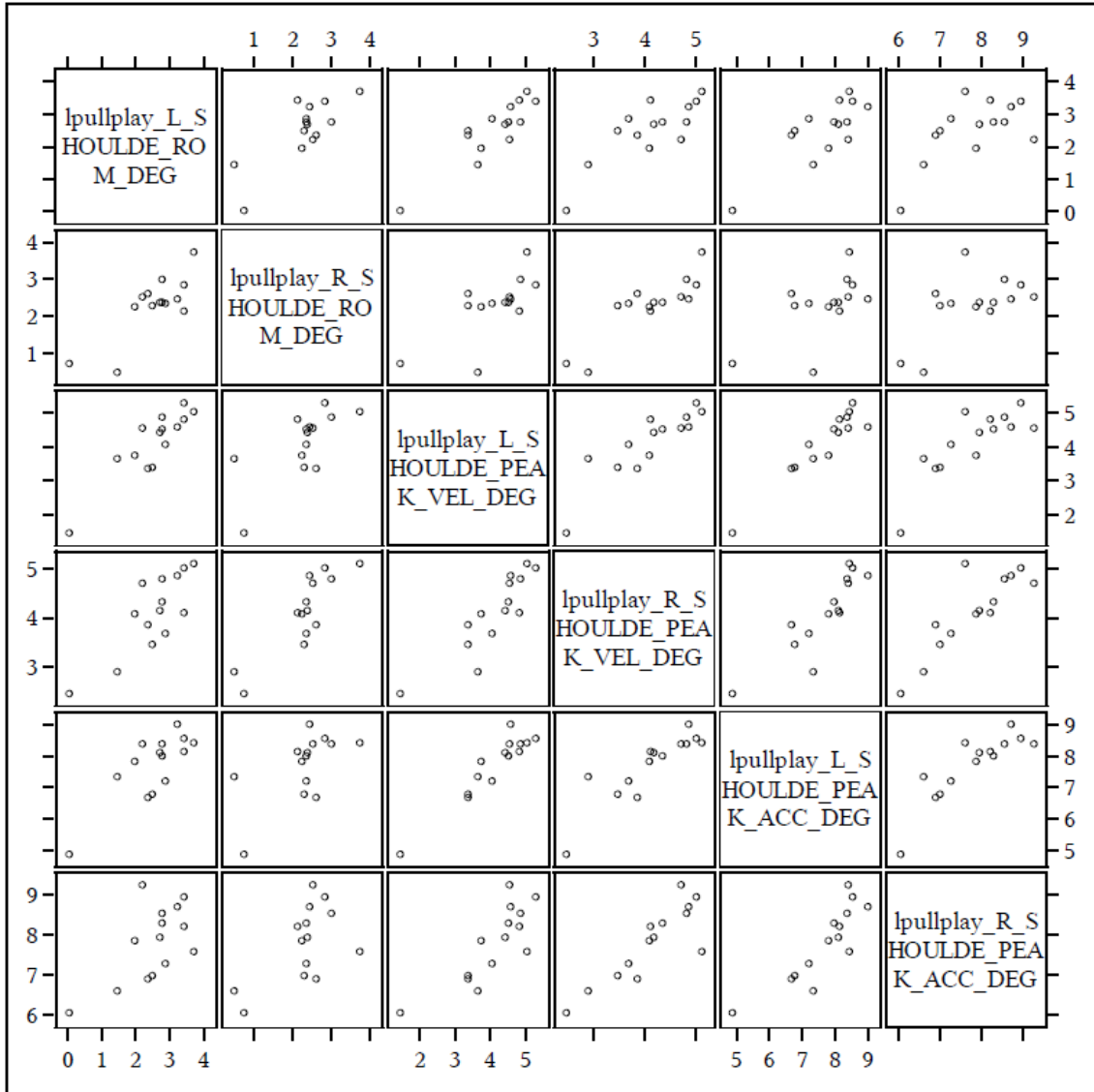*Figure IV.37*. Correlation Plot for Normal Population, Pull Play-Doh Apart, Elbow Component

Figure IV.38. Correlation Plot for Normal Population, Pull Play-Doh Apart, Shoulder Component

ACTIVITY 10: CUT PLAY-DOH® WITH KNIFE
KINEMATIC FOCUS: Wrist flexion/extension and radial/ulnar deviation
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: Mold Play-Doh into flat circle and instruct subject to cut the circle in a cyclic pattern for 10-20+ cycles (i.e. multiple cuts across the chord of the circle), using the dominant hand and ensuring that the arm is tracked fully.
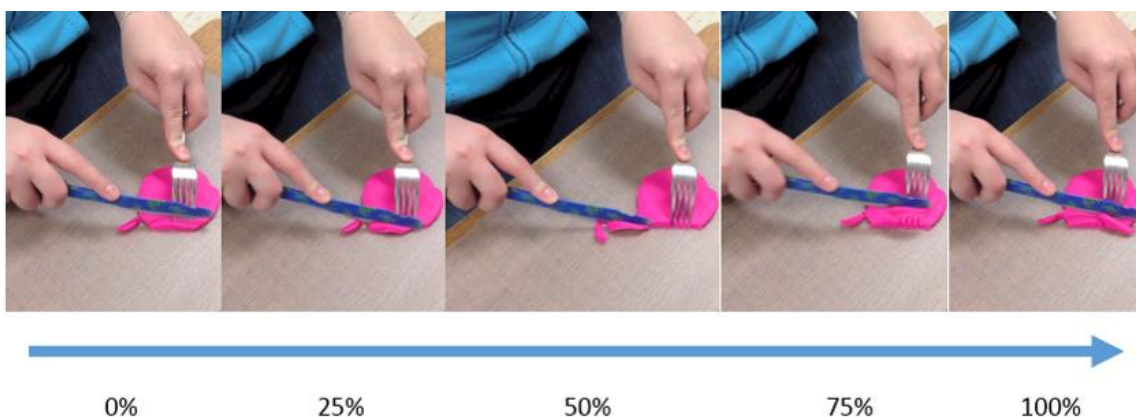
Figure IV.39. Activity Timeline for Cut Play-Doh with Knife

Table IV.39. Kinect-detected Parameters for Exemplar Subject, Cut Play-Doh with Knife

Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	5.791°	Right Wrist ROM	16.969°
Left Wrist Peak Velocity	24.762°/s	Right Wrist Peak Velocity	76.682°/s
Left Wrist Peak Acceleration	241.009°/s^2	Right Wrist Peak Acceleration	1280.837°/s^2
Left Elbow ROM	2.787°	Right Elbow ROM	30.588°
Left Elbow Peak Velocity	7.426°/s	Right Elbow Peak Velocity	94.324°/s
Left Elbow Peak Acceleration	67.013°/s^2	Right Elbow Peak Acceleration	477.282°/s^2
Left Shoulder ROM	0.973°	Right Shoulder ROM	18.094°
Left Shoulder Peak Velocity	2.710°/s	Right Shoulder Peak Velocity	54.759°/s
Left Shoulder Peak Acceleration	21.920°/s^2	Right Shoulder Peak Acceleration	301.628°/s^2

Figure IV.40. Kinematic Plots for Exemplar Subject, Cut Play-Doh with Knife

Table IV.40. Kinect Normal Population Statistics, Cut Play-Doh with Knife

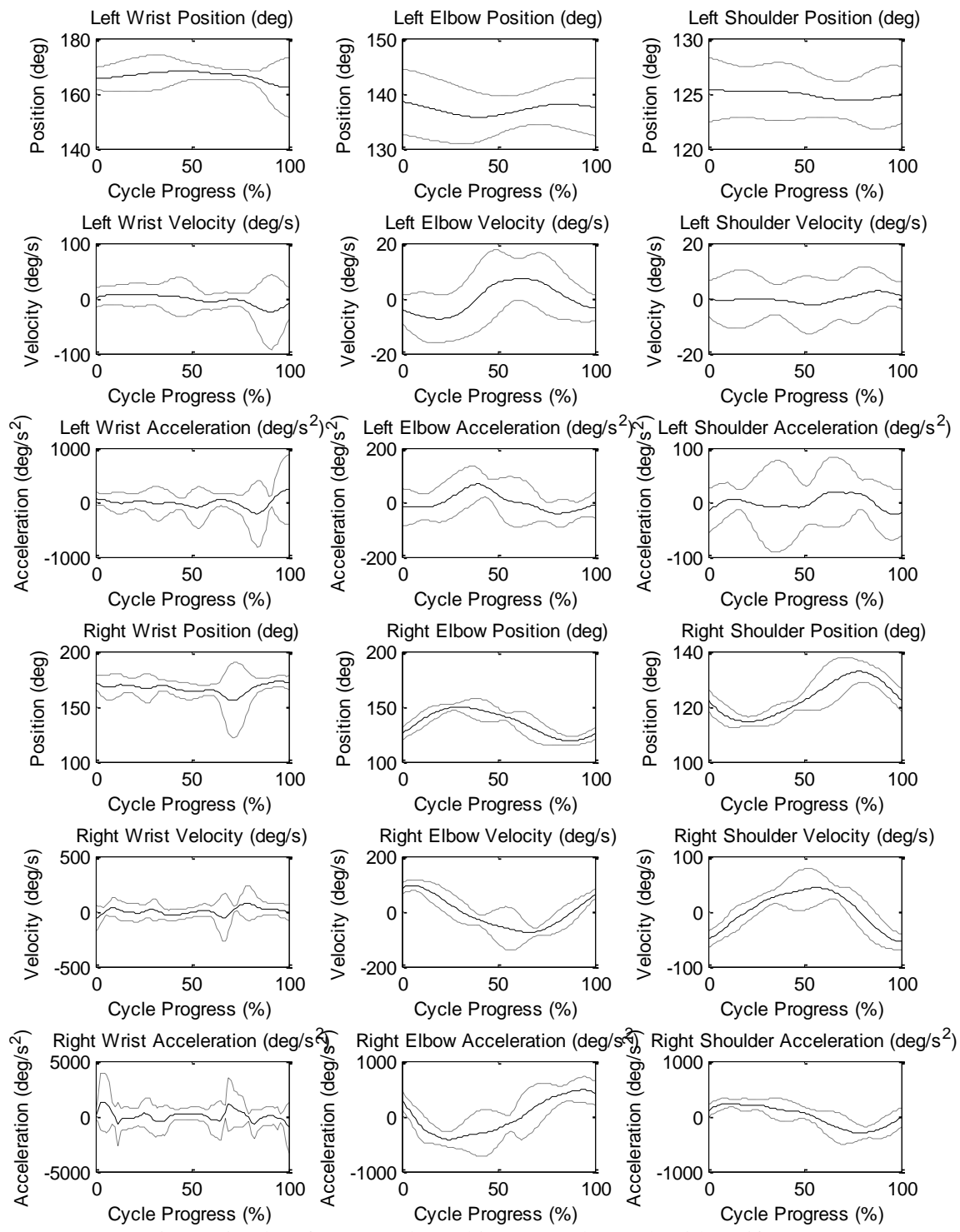| Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	28.93°	13.14°	5.96°	54.40°
Left Wrist Peak Velocity	n=12	246.57°/s	125.69°/s	39.67°/s	550.28°/s
Left Wrist Peak Acceleration	n=12	15336°/s^2	9242°/s^2	1923°/s^2	41018°/s^2
Left Elbow ROM	n=12	16.95°	8.62°	3.30°	28.75°
Left Elbow Peak Velocity	n=12	116.29°/s	64.27°/s	17.07°/s	233.05°/s
Left Elbow Peak Acceleration	n=12	5018°/s^2	2968°/s^2	1128°/s^2	10633°/s^2
Left Shoulder ROM	n=12	9.51°	6.62°	0.74°	21.93°
Left Shoulder Peak Velocity	n=12	59.73°/s	40.77°/s	2.91°/s	159.67°/s
Left Shoulder Peak Acceleration	n=12	2721°/s^2	2350°/s^2	63.16°/s^2	9059°/s^2
Right Wrist ROM	n=12	33.41°	18.64°	6.84°	72.80°
Right Wrist Peak Velocity	n=12	321.03°/s	181.27°/s	44.04°/s	646.14°/s
Right Wrist Peak Acceleration	n=12	20015°/s^2	14608°/s^2	2104°/s^2	59674°/s^2
Right Elbow ROM	n=12	25.41°	16.36°	2.63°	59.78°
Right Elbow Peak Velocity	n=12	173.68°/s	120.13°/s	11.96°/s	467.55°/s
Right Elbow Peak Acceleration	n=12	8376°/s^2	6980°/s^2	316.87°/s^2	25589°/s^2
Right Shoulder ROM	n=12	16.50°	12.02°	0.53°	40.43°
Right Shoulder Peak Velocity	n=12	130.94°/s	124.16°/s	5.66°/s	403.87°/s
Right Shoulder Peak Acceleration	n=12	4709°/s^2	4686°/s^2	163.42°/s^2	14572°/s^2

Table IV.41. Correlation Statistics, Cut Play-Doh® – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.61758	1.00000				
Left Wrist Peak Velocity	0.91648	0.63516	1.00000			
Right Wrist Peak Velocity	0.55165	0.91209	0.60000	1.00000		
Left Wrist Peak Acceleration	0.78462	0.39780	0.90769	0.34505	1.00000	
Right Wrist Peak Acceleration	0.52088	0.81538	0.56484	0.95604	0.30989	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.42. Correlation Statistics, Cut Play-Doh® – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	0.24835	1.00000				
Left Elbow Peak Velocity	0.84176	0.54286	1.00000			
Right Elbow Peak Velocity	0.19121	0.76703	0.46374	1.00000		
Left Elbow Peak Acceleration	0.60440	0.60879	0.92088	0.55165	1.00000	
Right Elbow Peak Acceleration	0.08132	0.59560	0.45495	0.75824	0.57363	1.00000

n=12; data converted to logarithmic scale prior to analysis

Table IV.43. Correlation Statistics, Cut Play-Doh® – Shoulder Component

Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	0.14286	1.00000				
Left Shoulder Peak Velocity	0.91209	0.39341	1.00000			
Right Shoulder Peak Velocity	0.41538	0.84615	0.64396	1.00000		
Left Shoulder Peak Acceleration	0.64835	0.61319	0.83736	0.88132	1.00000	
Right Shoulder Peak Acceleration	0.42857	0.68352	0.68352	0.93407	0.92527	1.00000

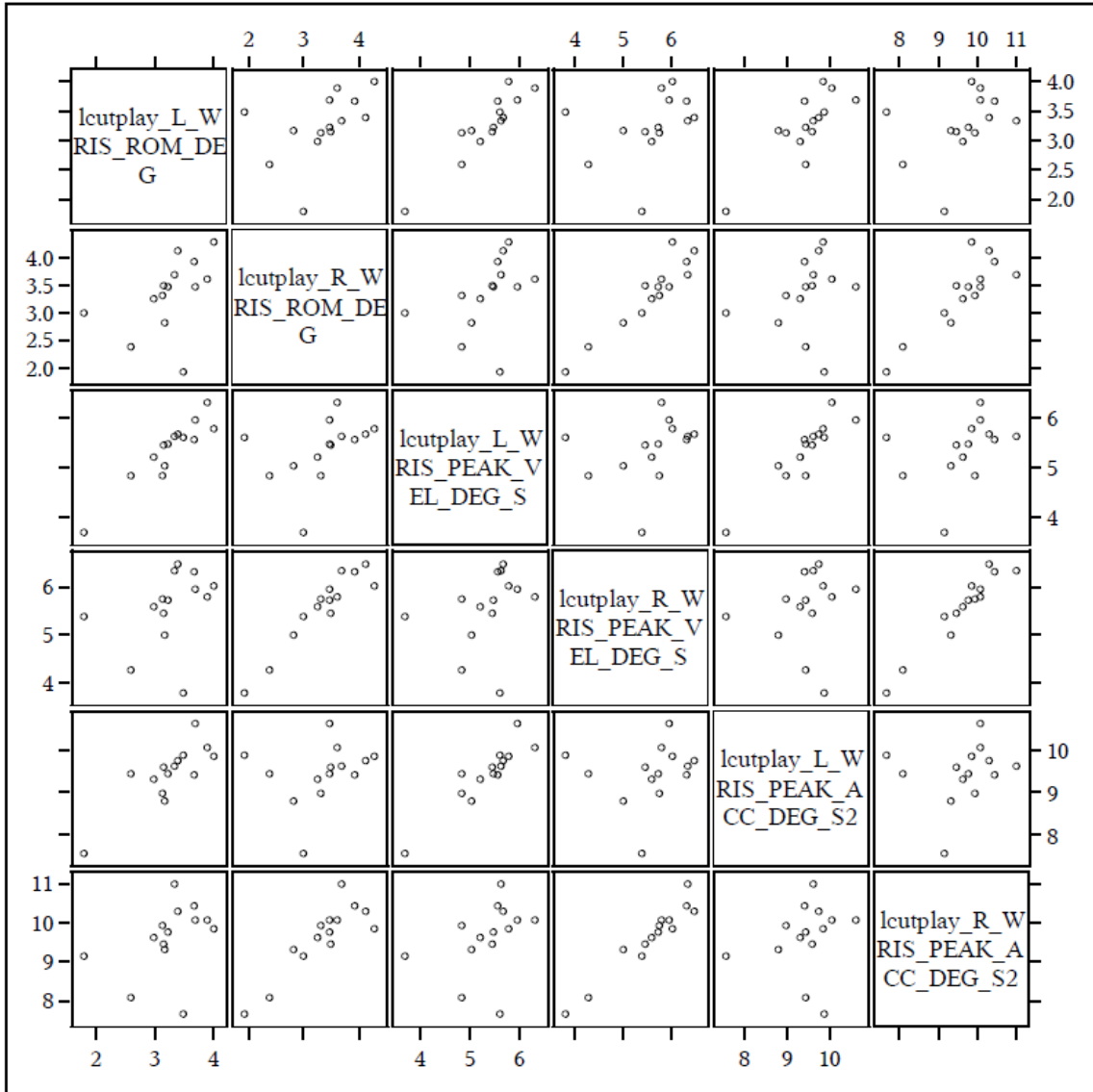n=12; data converted to logarithmic scale prior to analysis

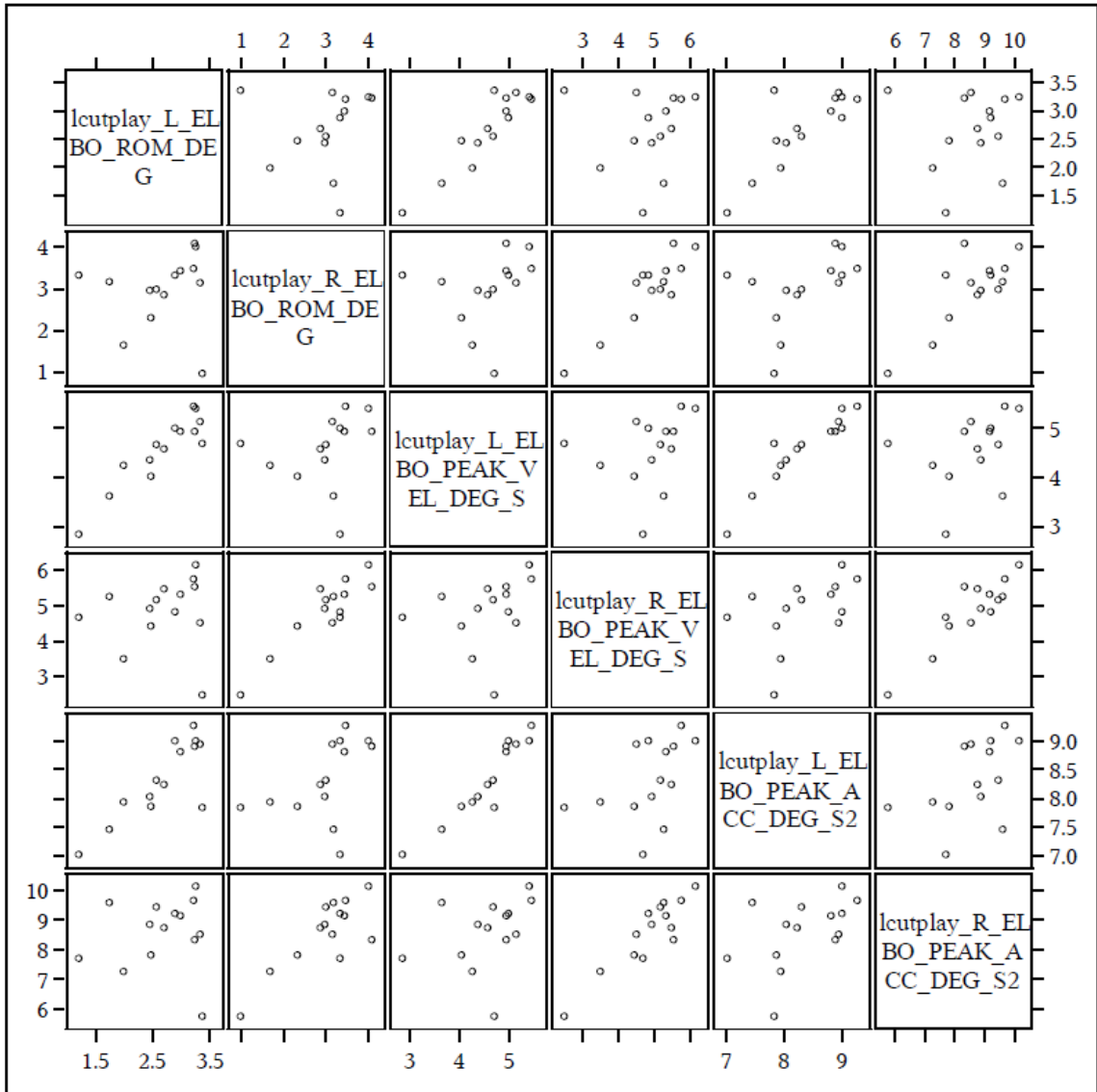*Figure IV.41*. Correlation Plot for Normal Population, Cut Play-Doh with Knife, Wrist Component

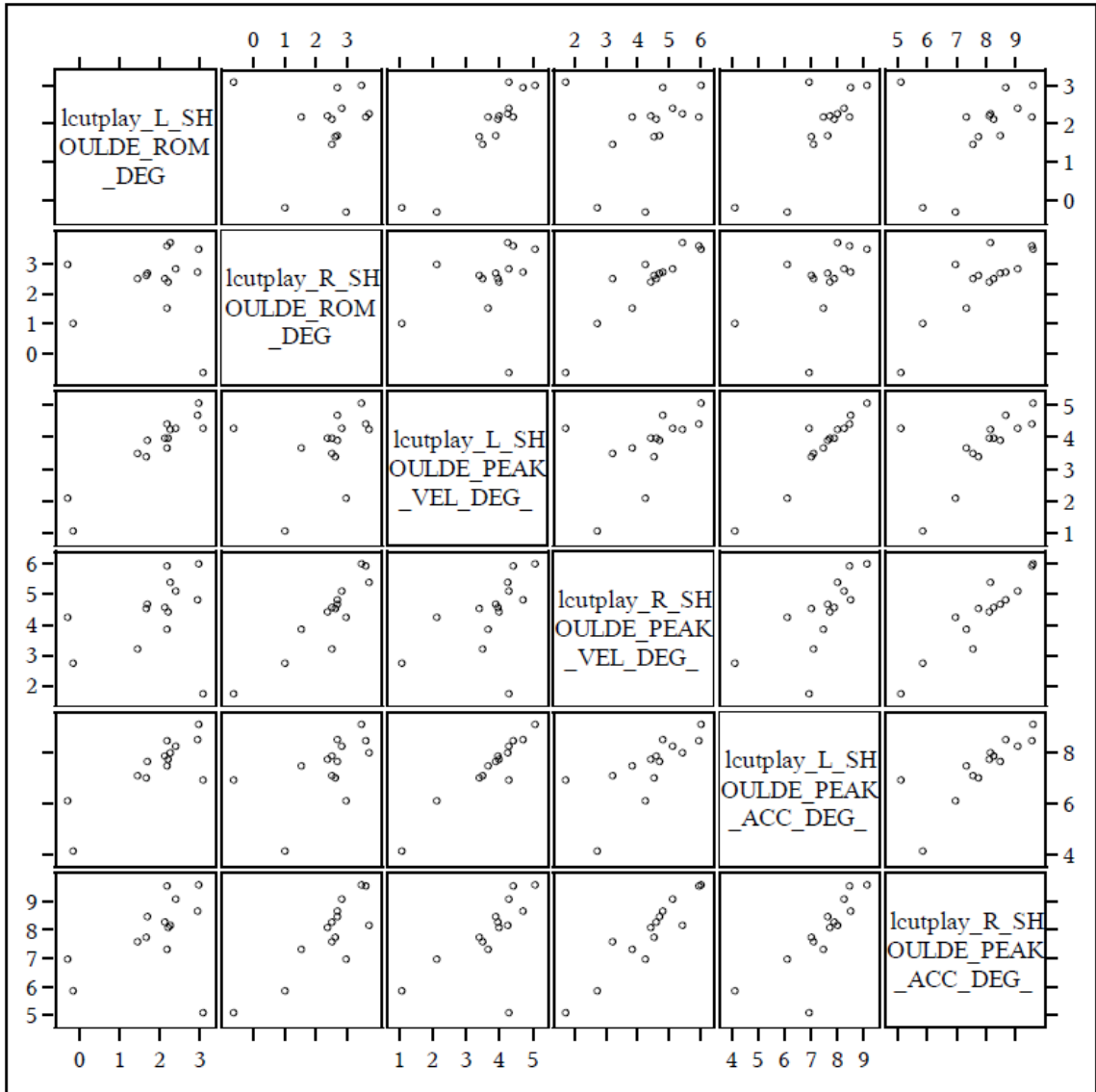*Figure IV.42*. Correlation Plot for Normal Population, Cut Play-Doh with Knife, Elbow Component

Figure IV.43. Correlation Plot for Normal Population, Cut Play-Doh with Knife, Shoulder Component

ACTIVITY 11: THROW PING-PONG BALL
KINEMATIC FOCUS: Wrist flexion/extension and radial/ulnar deviation, elbow
flexion/extension
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: Instruct subject to throw ping-pong balls overhand in a cyclic pattern for
10-20+ cycles using the dominant hand, ensuring that the arm is tracked fully.

Figure IV.44. Activity Timeline for Throw Ping-Pong Ball

Table IV.44. Kinect-detected Parameters for Exemplar Subject, Throw Ping-Pong Ball

| Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	1.551°	Right Wrist ROM	14.475°
Left Wrist Peak Velocity	6.242°/s	Right Wrist Peak Velocity	119.696°/s
Left Wrist Peak Acceleration	77.406°/s^2	Right Wrist Peak Acceleration	2813.389°/s^2
Left Elbow ROM	8.951°	Right Elbow ROM	80.487°
Left Elbow Peak Velocity	23.848°/s	Right Elbow Peak Velocity	245.484°/s
Left Elbow Peak Acceleration	124.282°/s^2	Right Elbow Peak Acceleration	2211.203°/s^2
Left Shoulder ROM	6.812°	Right Shoulder ROM	39.706°
Left Shoulder Peak Velocity	20.564°/s	Right Shoulder Peak Velocity	231.434°/s
Left Shoulder Peak Acceleration	149.281°/s^2	Right Shoulder Peak Acceleration	3062.655°/s^2
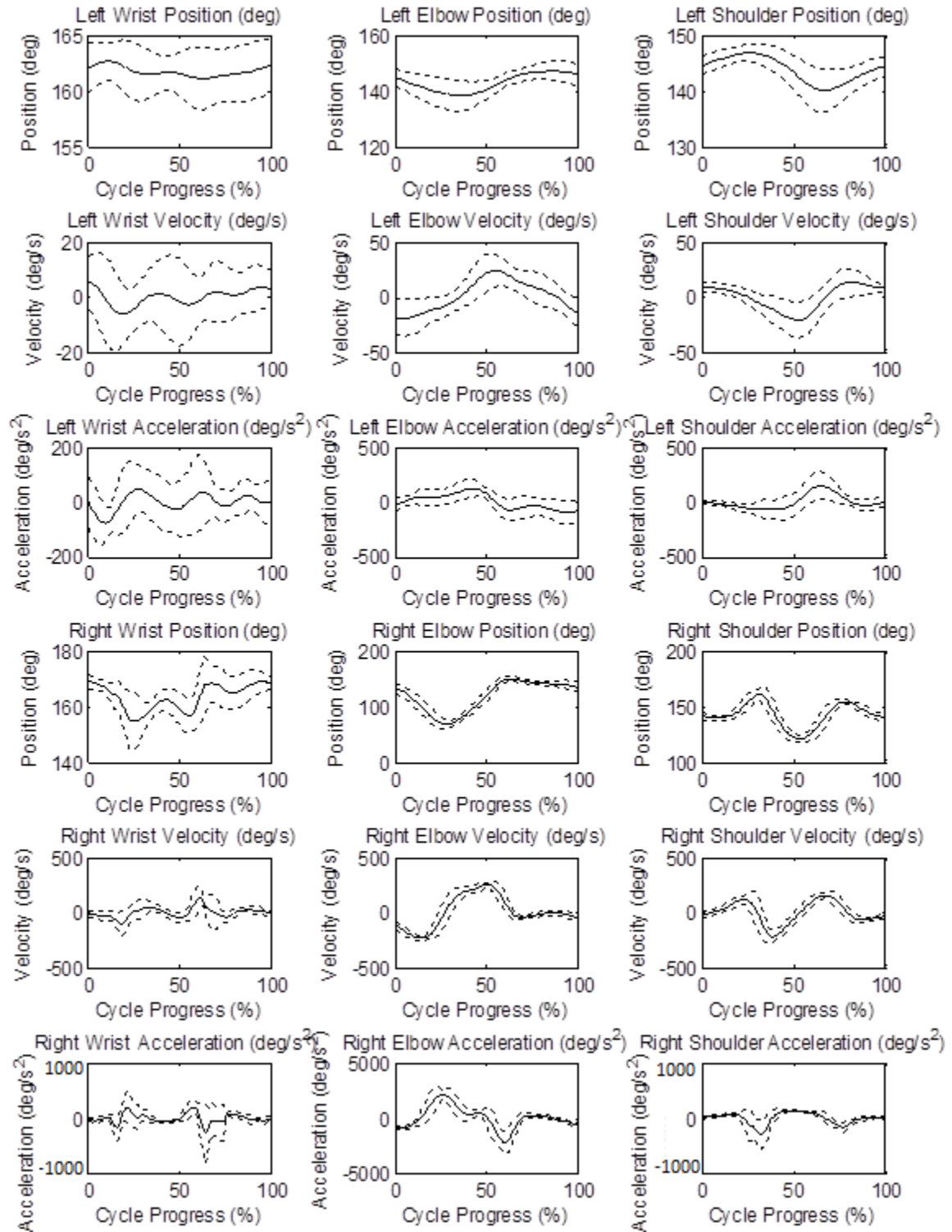
Figure IV.45. Kinematic Plots for Exemplar Subject, Throw Ping-Pong Ball

Table IV.45. Kinect Normal Population Statistics, Throw Ping-Pong Ball

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	23.39°	9.67°	3.05°	44.23°
Left Wrist Peak Velocity	n=12	201.33°/s	93.52°/s	28.59°/s	447.88°/s
Left Wrist Peak Acceleration	n=12	11762°/s^2	7765°/s^2	1246°/s^2	36443°/s^2
Left Elbow ROM	n=12	31.17°	30.10°	9.03°	111.32°
Left Elbow Peak Velocity	n=12	145.55°/s	94.69°/s	44.69°/s	428.36°/s
Left Elbow Peak Acceleration	n=12	5869°/s^2	3433°/s^2	866.44°/s^2	15488°/s^2
Left Shoulder ROM	n=12	14.81°	8.77°	7.09°	43.46°
Left Shoulder Peak Velocity	n=12	78.34°/s	26.99°/s	32.44°/s	126.45°/s
Left Shoulder Peak Acceleration	n=12	4010°/s^2	2747°/s^2	910.95°/s^2	11506°/s^2
Right Wrist ROM	n=12	32.75°	13.94°	1.36°	62.70°
Right Wrist Peak Velocity	n=12	268.86°/s	127.89°/s	3.63°/s	555.71°/s
Right Wrist Peak Acceleration	n=12	17510°/s^2	9580°/s^2	57.49°/s^2	41250°/s^2
Right Elbow ROM	n=12	40.30°	22.24°	3.10°	98.93°
Right Elbow Peak Velocity	n=12	228.56°/s	117.57°/s	17.04°/s	481.33°/s
Right Elbow Peak Acceleration	n=12	7017°/s^2	3023°/s^2	440.19°/s^2	11763°/s^2
Right Shoulder ROM	n=12	21.66°	10.79°	6.24°	47.72°
Right Shoulder Peak Velocity	n=12	122.52°/s	58.96°/s	35.48°/s	283.97°/s
Right Shoulder Peak Acceleration	n=12	4137°/s^2	2160°/s^2	954.28°/s^2	8827°/s^2

Table IV.46. Correlation Statistics, Throw Ball – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.36703	1.00000				
Left Wrist Peak Velocity	0.66484	0.48901	1.00000			
Right Wrist Peak Velocity	0.15604	0.54725	0.22527	1.00000		
Left Wrist Peak Acceleration	0.50549	0.37363	0.43956	0.32967	1.00000	
Right Wrist Peak Acceleration	0.12088	0.59341	0.14685	0.69780	0.39860	1.00000

n=12

Table IV.47. Correlation Statistics, Throw Ball – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	-0.31429	1.00000				
Left Elbow Peak Velocity	0.91758	-0.08791	1.00000			
Right Elbow Peak Velocity	-0.32308	0.90330	-0.20330	1.00000		
Left Elbow Peak Acceleration	0.52747	0.30220	0.58791	0.19231	1.00000	
Right Elbow Peak Acceleration	-0.52088	0.14286	-0.56044	0.34505	-0.22527	1.00000

n=12

Table IV.48. Correlation Statistics, Throw Ball – Shoulder Component

| Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	-0.42308	1.00000				
Left Shoulder Peak Velocity	0.63736	-0.57363	1.00000			
Right Shoulder Peak Velocity	-0.26923	0.83736	-0.43736	1.00000		
Left Shoulder Peak Acceleration	0.56593	-0.51209	0.79780	-0.17363	1.00000	
Right Shoulder Peak Acceleration	-0.43956	0.38385	-0.24396	0.58681	0.16484	1.00000

n=12
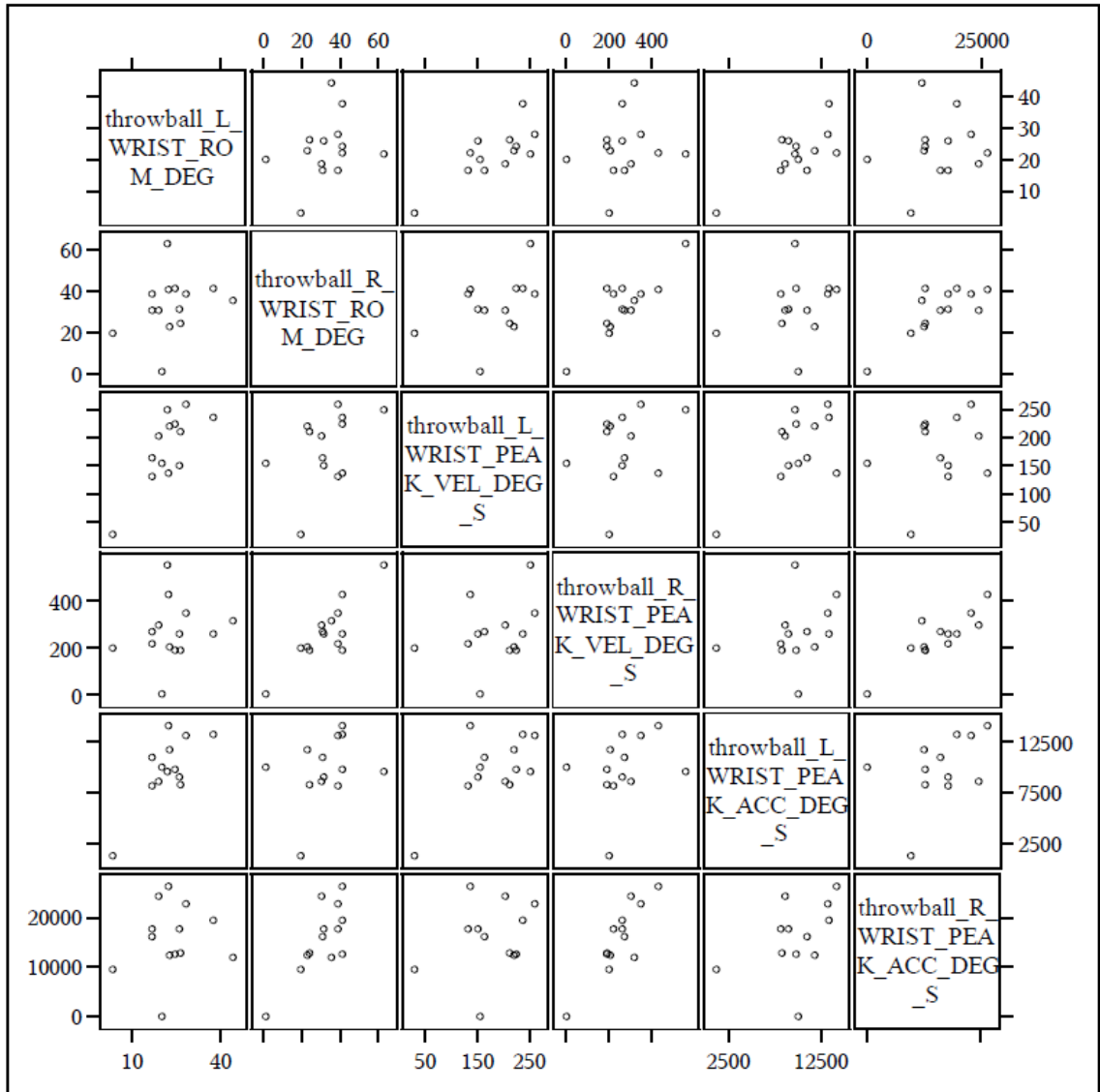
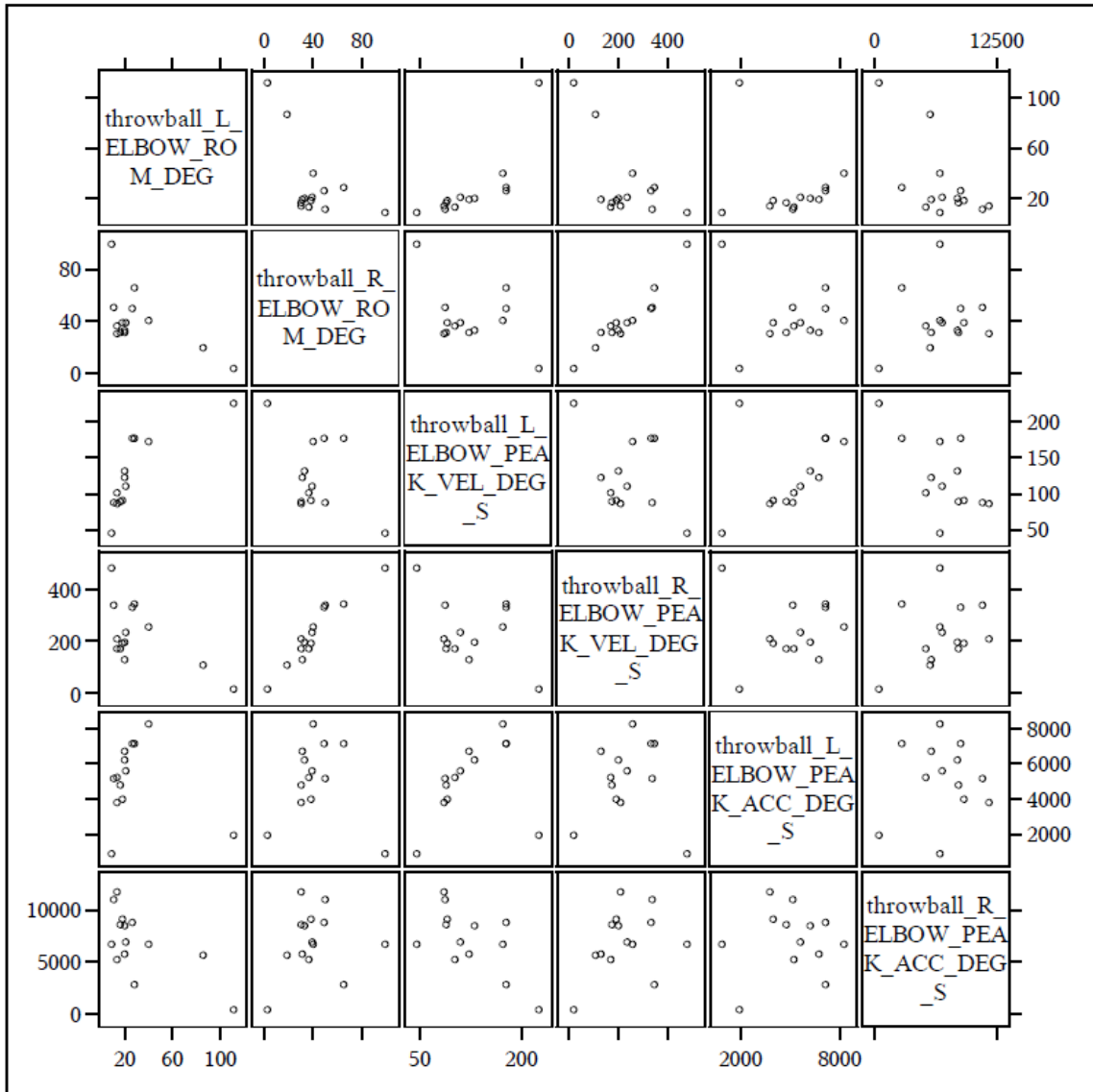*Figure IV.46.* Correlation Plot for Normal Population, Throw Ping-Pong Ball, Wrist Component

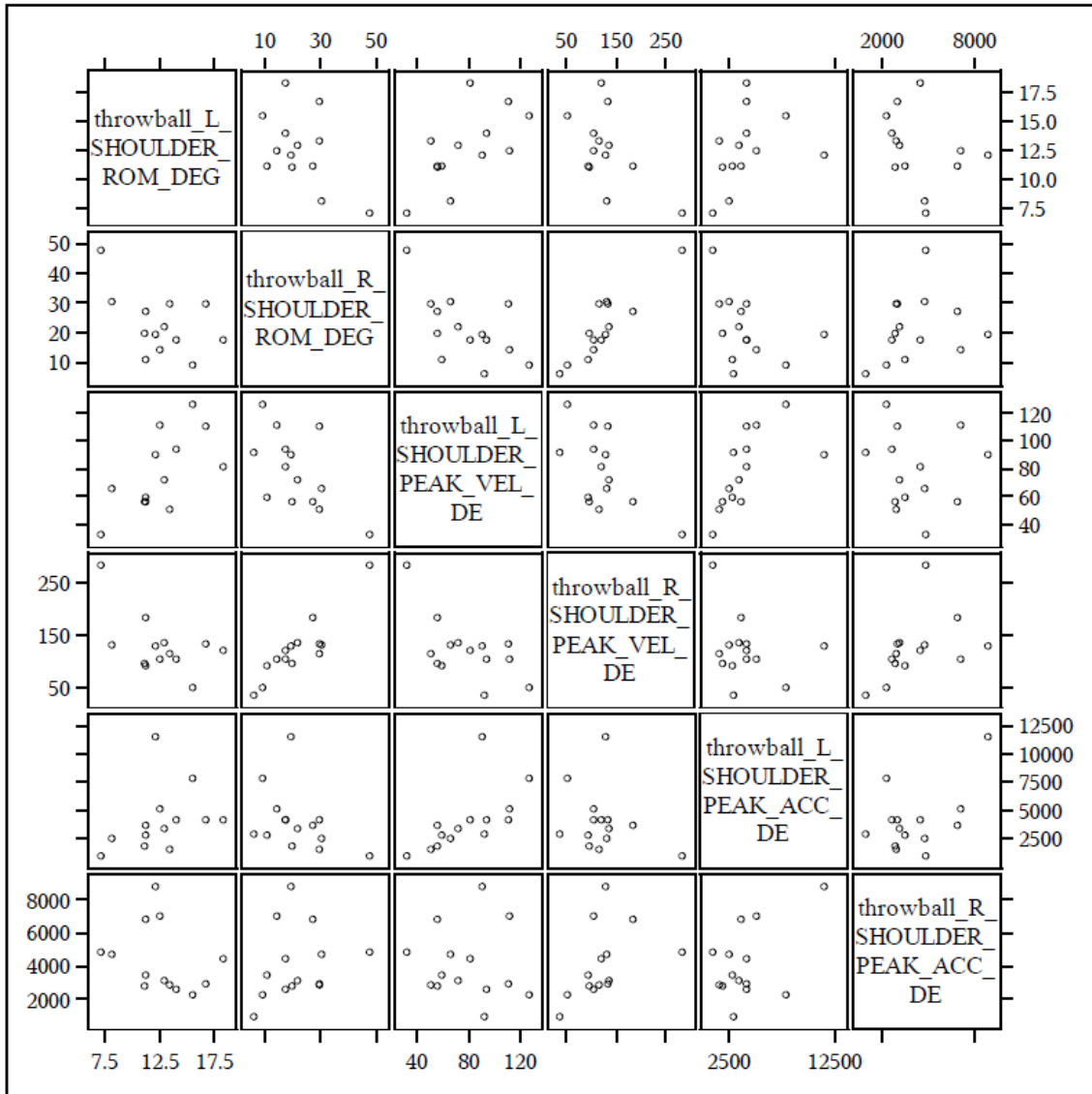*Figure IV.47*. Correlation Plot for Normal Population, Throw Ping-Pong Ball, Elbow Component

Figure IV.48. Correlation Plot for Normal Population, Throw Ping-Pong Ball, Shoulder Component

ACTIVITY 12: PLACE STICKER ON LARGE BALL
KINEMATIC FOCUS: Elbow flexion/extension
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: Place ball at arm's length from subject and provide subject with a sheet of stickers. Instruct subject to place stickers on ball using dominant hand in a repeating, cyclic pattern for 10-20+ cycles, holding the sticker sheet in non-dominant hand, while ensuring that the arm is tracked fully.
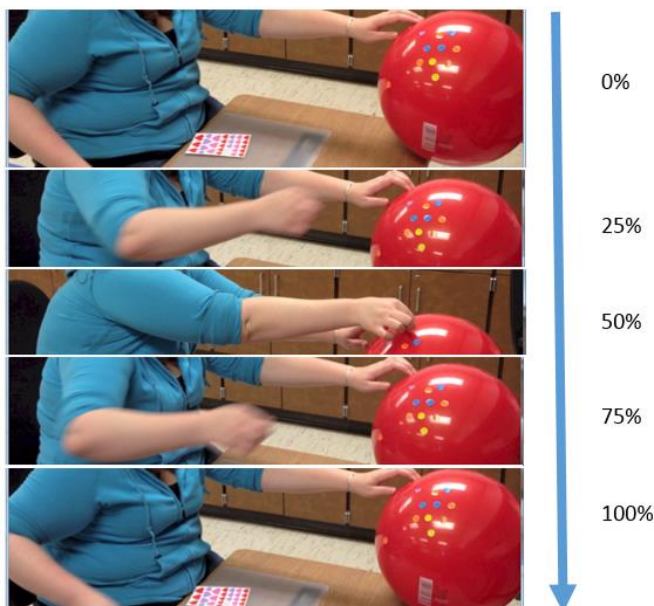

Figure IV.49. Activity Timeline for Place Sticker on Ball

Table IV.49. Kinect-detected Parameters for Exemplar Subject, Place Sticker on Ball

| Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	3.737°	Right Wrist ROM	12.480°
Left Wrist Peak Velocity	11.205°/s	Right Wrist Peak Velocity	74.116°/s
Left Wrist Peak Acceleration	66.665°/s^2	Right Wrist Peak Acceleration	696.837°/s^2
Left Elbow ROM	2.246°	Right Elbow ROM	73.852°
Left Elbow Peak Velocity	8.551°/s	Right Elbow Peak Velocity	204.110°/s
Left Elbow Peak Acceleration	67.030°/s^2	Right Elbow Peak Acceleration	1443.619°/s^2
Left Shoulder ROM	1.987°	Right Shoulder ROM	10.539°
Left Shoulder Peak Velocity	4.774°/s	Right Shoulder Peak Velocity	30.754°/s
Left Shoulder Peak Acceleration	23.334°/s^2	Right Shoulder Peak Acceleration	310.373°/s^2
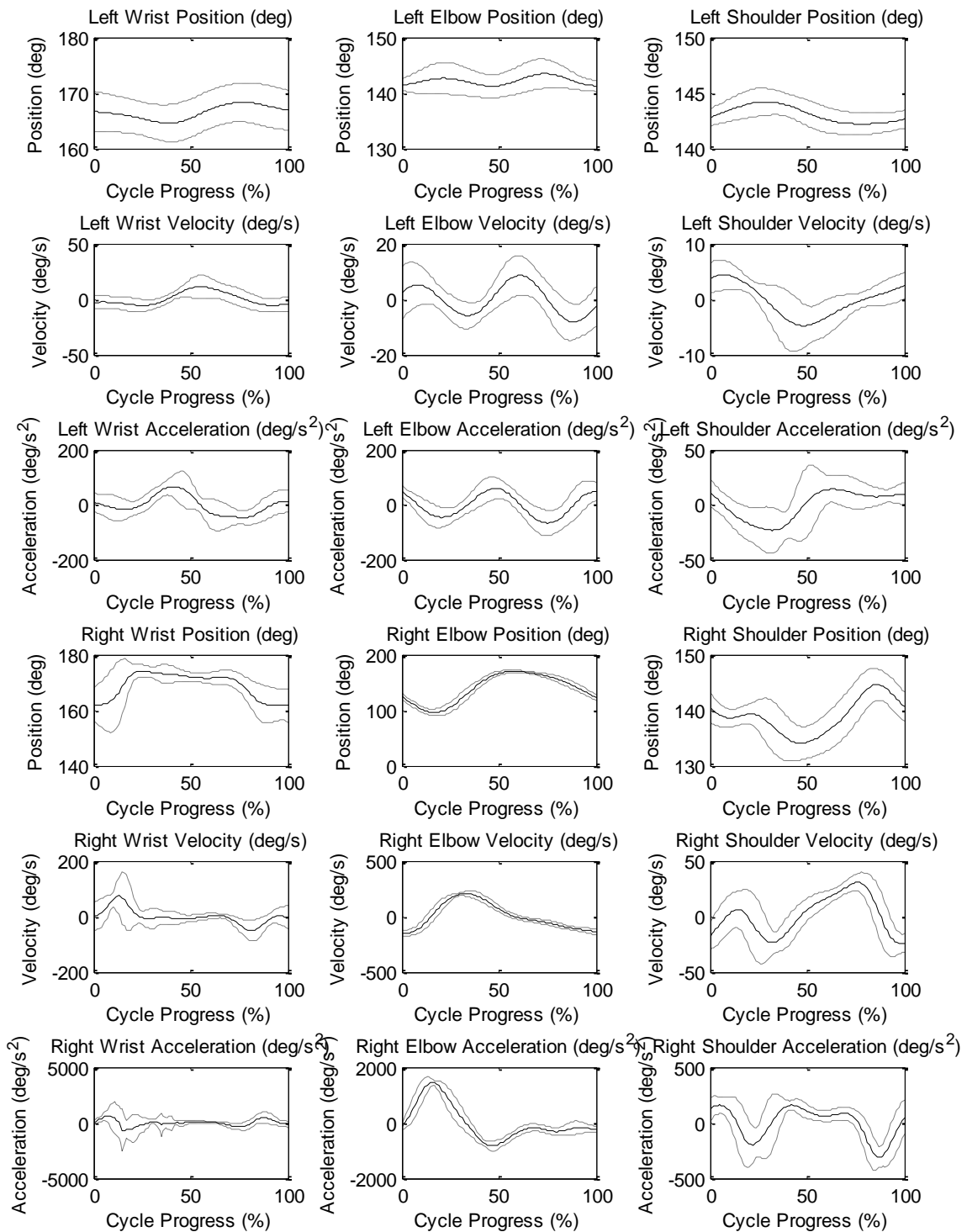
Figure IV.50. Kinematic Plots for Exemplar Subject, Place Sticker on Ball

Table IV.50. Kinect Normal Population Statistics, Place Sticker on Ball

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	29.42°	18.54°	4.04°	70.14°
Left Wrist Peak Velocity	n=12	231.96°/s	180.24°/s	15.73°/s	599.10°/s
Left Wrist Peak Acceleration	n=12	14245°/s^2	10266°/s^2	215.49°/s^2	36480°/s^2
Left Elbow ROM	n=12	26.30°	22.12°	1.93°	87.02°
Left Elbow Peak Velocity	n=12	128.63°/s	80.45°/s	7.17°/s	360.58°/s
Left Elbow Peak Acceleration	n=12	5364°/s^2	3375°/s^2	67.43°/s^2	11567°/s^2
Left Shoulder ROM	n=12	13.23°	8.66°	0.82°	30.33°
Left Shoulder Peak Velocity	n=12	67.23°/s	44.36°/s	2.81°/s	142.54°/s
Left Shoulder Peak Acceleration	n=12	3844°/s^2	4836°/s^2	56.59°/s^2	19309°/s^2
Right Wrist ROM	n=12	39.96°	26.01°	0.29°	117.07°
Right Wrist Peak Velocity	n=12	307.83°/s	138.47°/s	0.70°/s	619.17°/s
Right Wrist Peak Acceleration	n=12	20742°/s^2	12026°/s^2	7.44°/s^2	43637°/s^2
Right Elbow ROM	n=12	45.02°	19.94°	0.17°	76.32°
Right Elbow Peak Velocity	n=12	202.65°/s	83.11°/s	0.41°/s	317.98°/s
Right Elbow Peak Acceleration	n=12	9256°/s^2	7009°/s^2	5.91°/s^2	28075°/s^2
Right Shoulder ROM	n=12	16.89°	7.79°	0.22°	27.91°
Right Shoulder Peak Velocity	n=12	83.49°/s	38.21°/s	0.54°/s	123.34°/s
Right Shoulder Peak Acceleration	n=12	4471°/s^2	4974°/s^2	15.51°/s^2	20703°/s^2

Table IV.51. Correlation Statistics, Place Sticker on Ball – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.47692	1.00000				
Left Wrist Peak Velocity	0.90769	0.49011	1.00000			
Right Wrist Peak Velocity	0.31868	0.56923	0.30549	1.00000		
Left Wrist Peak Acceleration	0.75385	0.58242	0.86813	0.32747	1.00000	
Right Wrist Peak Acceleration	0.34945	0.62637	0.30989	0.84615	0.27912	1.00000

n=12

Table IV.52. Correlation Statistics, Place Sticker on Ball – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	-0.14286	1.00000				
Left Elbow Peak Velocity	0.59890	0.07692	1.00000			
Right Elbow Peak Velocity	-0.36264	0.63956	0.16484	1.00000		
Left Elbow Peak Acceleration	0.45055	0.11648	0.94505	0.23516	1.00000	
Right Elbow Peak Acceleration	0.11538	0.11648	0.73077	0.50330	0.72747	1.00000

n=12

Table IV.53. Correlation Statistics, Place Sticker on Ball – Shoulder Component

| Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	0.63516	1.00000				
Left Shoulder Peak Velocity	0.84615	0.62637	1.00000			
Right Shoulder Peak Velocity	0.41538	0.60000	0.09890	1.00000		
Left Shoulder Peak Acceleration	0.72527	0.49451	0.83516	0.00549	1.00000	
Right Shoulder Peak Acceleration	0.60440	0.73077	0.39011	0.85714	0.26923	1.00000

n=12
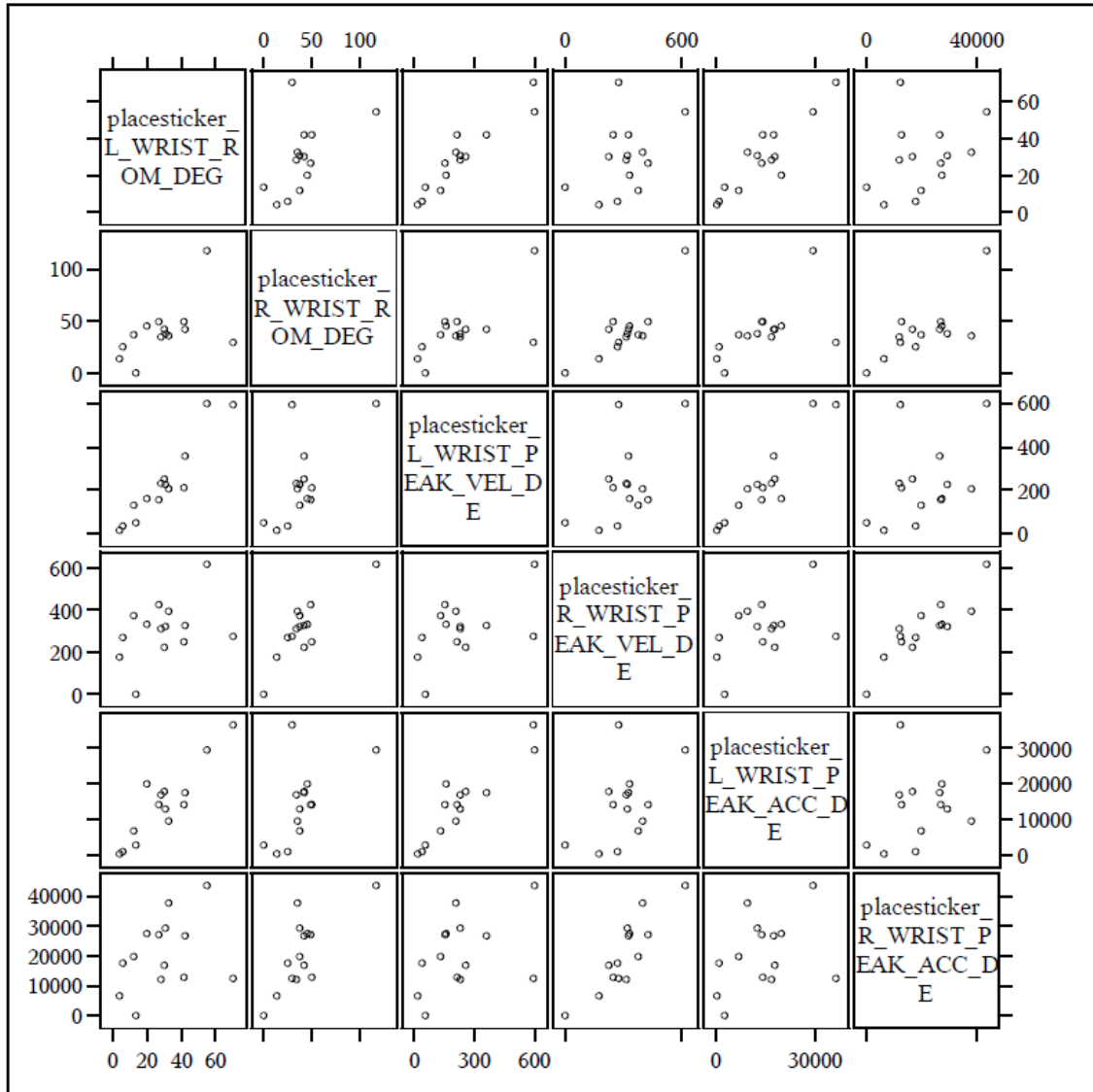
Figure IV.51. Correlation Plot for Normal Population, Place Sticker on Ball, Wrist Component
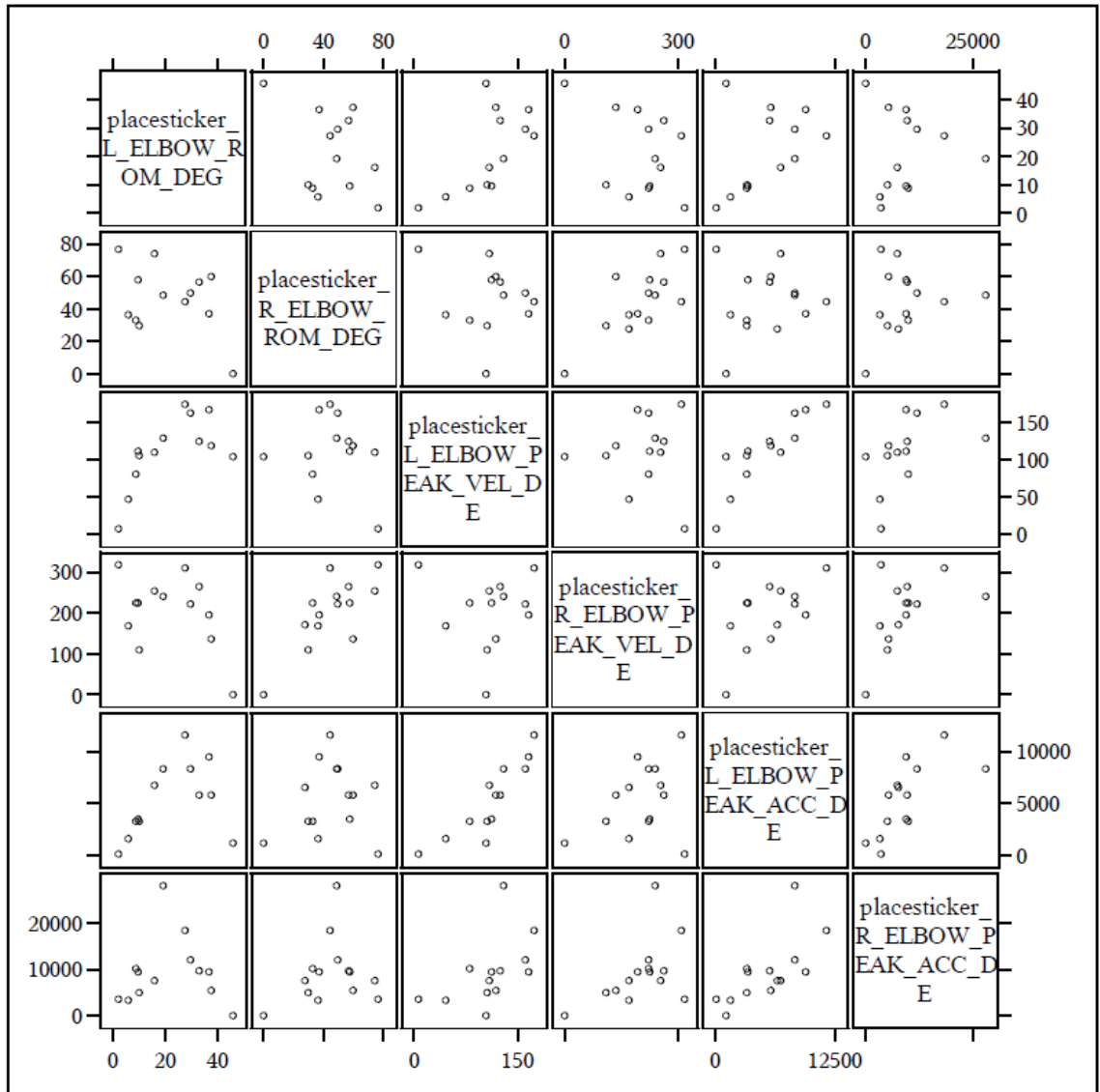
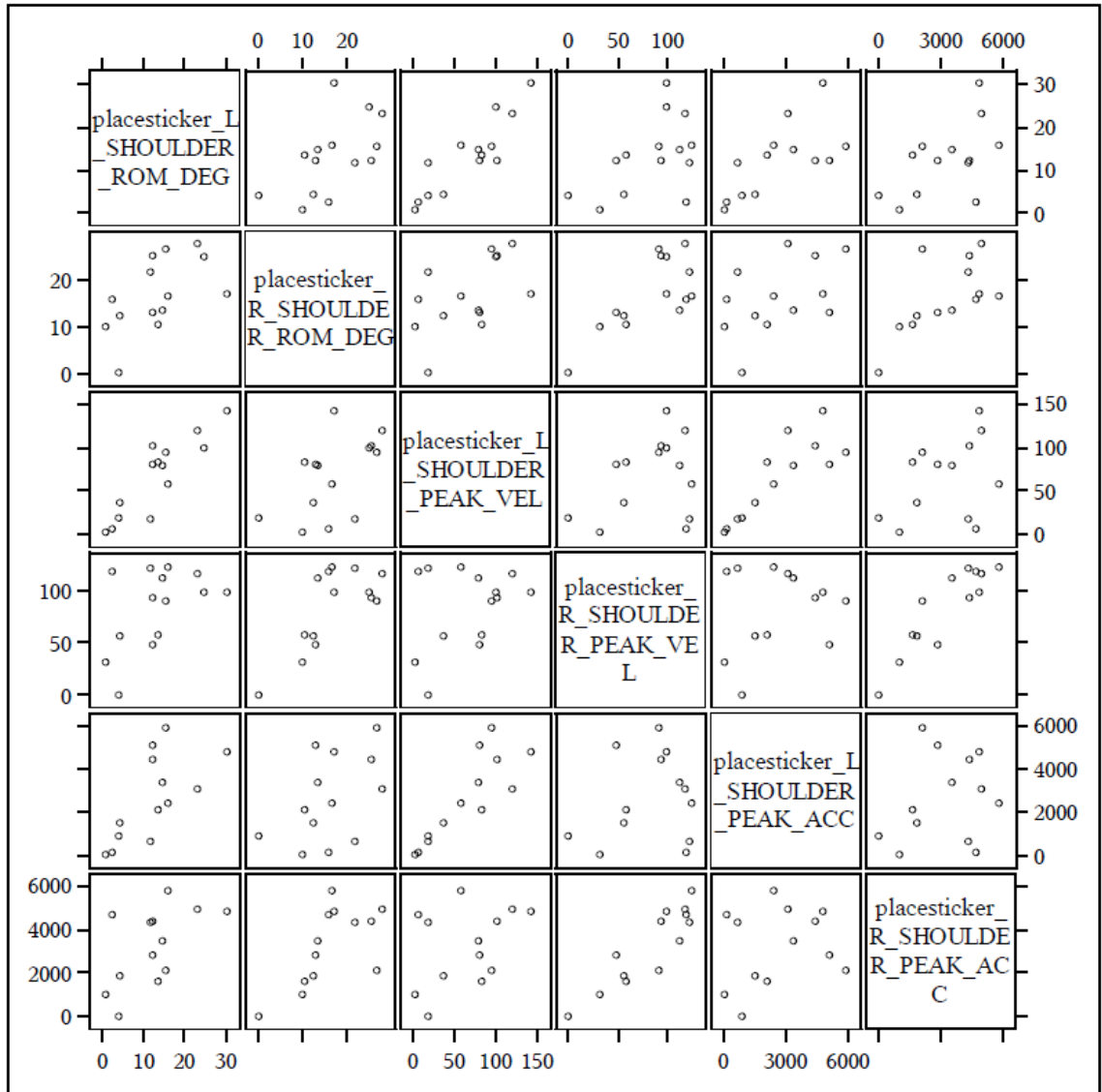*Figure IV.52*. Correlation Plot for Normal Population, Place Sticker on Ball, Elbow Component

Figure IV.53. Correlation Plot for Normal Population, Place Sticker on Ball, Shoulder Component

ACTIVITY 13: PUT SOCKS ON OR FASTEN SHOE
KINEMATIC FOCUS: Elbow flexion/extension
KINECT SYSTEM SETUP: Upper extremity kinematics software – seated or standing mode
TESTING PROTOCOL: With subject seated and with one shoe and sock removed, instruct subject to put on and remove the sock in a cyclic repeating pattern, returning to upright seated posture between each cycle, while ensuring that both arms are fully tracked throughout the testing. Repeat for 10-20+ cycles.
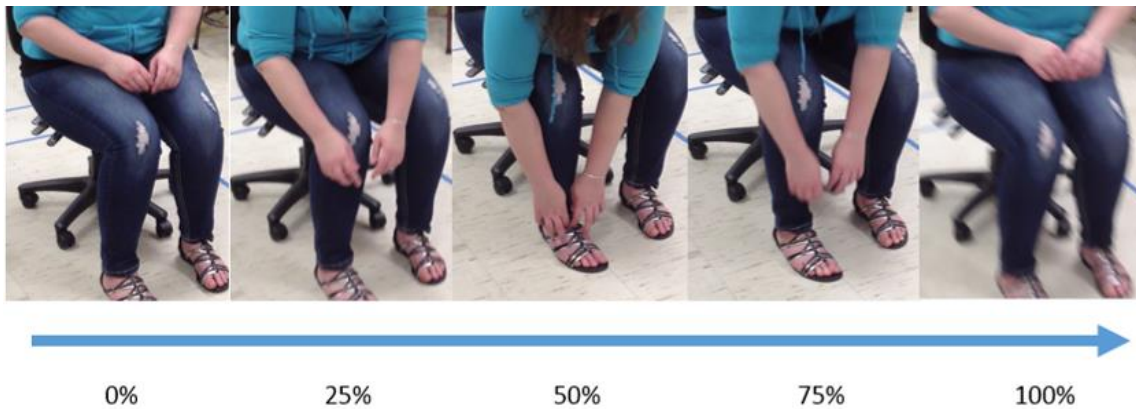

Figure IV.54. Activity Timeline for Fasten Shoe

Table IV.54. Kinect-detected Parameters for Exemplar Subject, Fasten Shoe

| Metric	Detected Value	Metric	Detected Value
Left Wrist ROM	7.533°	Right Wrist ROM	8.984°
Left Wrist Peak Velocity	36.552°/s	Right Wrist Peak Velocity	34.366°/s
Left Wrist Peak Acceleration	339.792°/s^2	Right Wrist Peak Acceleration	393.012°/s^2
Left Elbow ROM	49.132°	Right Elbow ROM	45.254°
Left Elbow Peak Velocity	107.885°/s	Right Elbow Peak Velocity	107.658°/s
Left Elbow Peak Acceleration	1146.770°/s^2	Right Elbow Peak Acceleration	612.456°/s^2
Left Shoulder ROM	25.147°	Right Shoulder ROM	23.076°
Left Shoulder Peak Velocity	53.474°/s	Right Shoulder Peak Velocity	50.720°/s
Left Shoulder Peak Acceleration	278.993°/s^2	Right Shoulder Peak Acceleration	245.021°/s^2
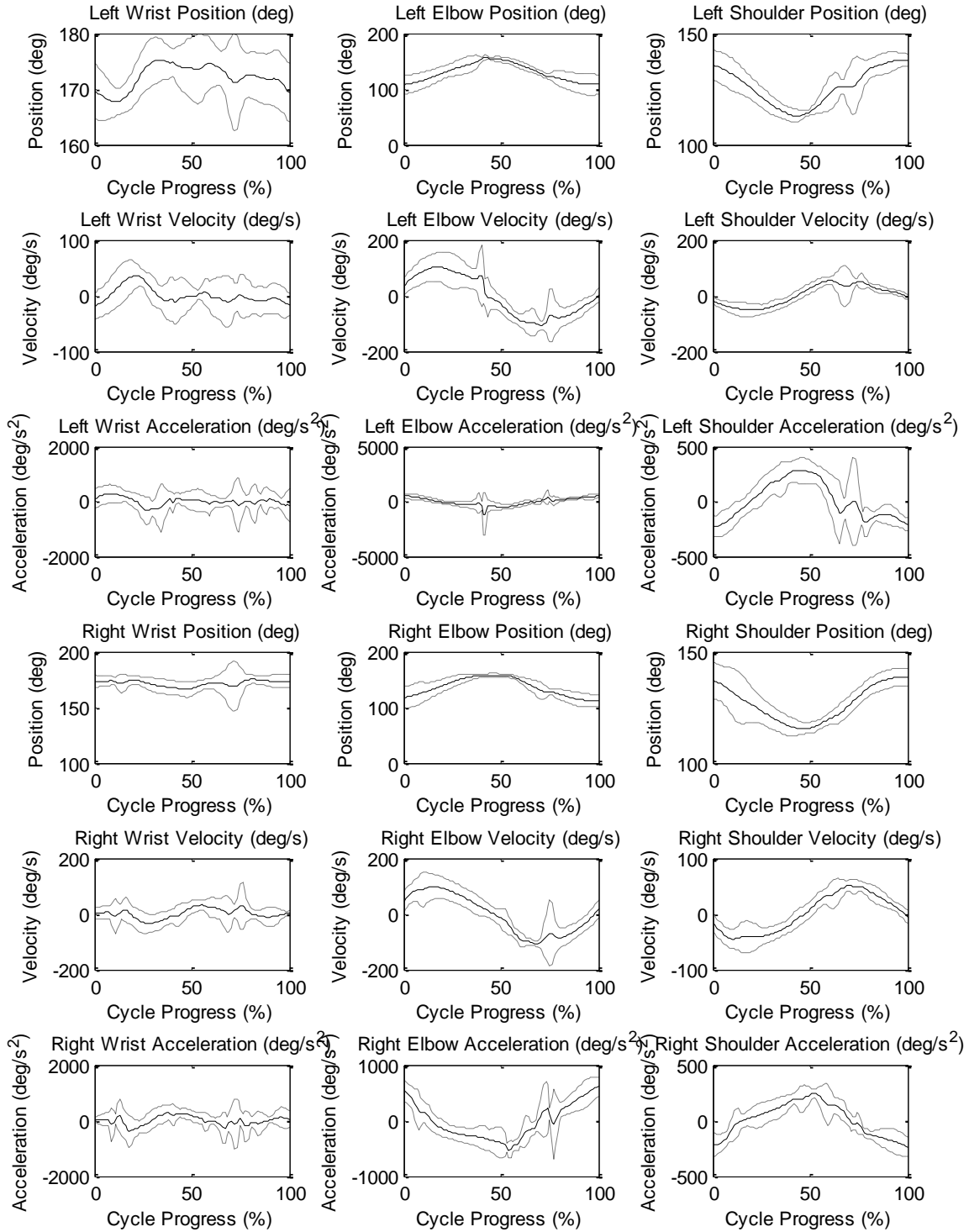
Figure IV.55. Kinematic Plots for Exemplar Subject, Fasten Shoe

Table IV.55. Kinect Normal Population Statistics, Fasten Shoe

Metric	n	Mean	Std Dev.	Minimum	Maximum
Left Wrist ROM	n=12	36.91°	16.46°	9.95°	74.11°
Left Wrist Peak Velocity	n=12	281.21°/s	166.55°/s	70.94°/s	697.76°/s
Left Wrist Peak Acceleration	n=12	17858°/s^2	11744°/s^2	3046°/s^2	47575°/s^2
Left Elbow ROM	n=12	46.38°	19.05°	20.98°	89.36°
Left Elbow Peak Velocity	n=12	297.52°/s	130.98°/s	52.01°/s	579.14°/s
Left Elbow Peak Acceleration	n=12	14280°/s^2	8810°/s^2	585.23°/s^2	32153°/s^2
Left Shoulder ROM	n=12	39.36°	12.14°	14.17°	58.00°
Left Shoulder Peak Velocity	n=12	205.57°/s	118.14°/s	38.33°/s	504.81°/s
Left Shoulder Peak Acceleration	n=12	7187°/s^2	5554°/s^2	915.75°/s^2	22912°/s^2
Right Wrist ROM	n=12	38.74°	17.77°	14.18°	75.51°
Right Wrist Peak Velocity	n=12	342.27°/s	154.59°/s	101.69°/s	629.59°/s
Right Wrist Peak Acceleration	n=12	19686°/s^2	12298°/s^2	2134°/s^2	43032°/s^2
Right Elbow ROM	n=12	53.30°	24.14°	22.21°	90.63°
Right Elbow Peak Velocity	n=12	322.19°/s	157.55°/s	72.65°/s	628.56°/s
Right Elbow Peak Acceleration	n=12	17932°/s^2	9567°/s^2	1671°/s^2	33868°/s^2
Right Shoulder ROM	n=12	40.94°	15.92°	6.55°	61.22°
Right Shoulder Peak Velocity	n=12	197.02°/s	112.02°/s	34.74°/s	415.69°/s
Right Shoulder Peak Acceleration	n=12	10661°/s^2	11816°/s^2	690.68°/s^2	47703°/s^2

Table IV.56. Correlation Statistics, Fasten Shoe – Wrist Component

Spearman Correlation Coefficients	Left Wrist ROM	Right Wrist ROM	Left Wrist Peak Velocity	Right Wrist Peak Velocity	Left Wrist Peak Acceleration	Right Wrist Peak Acceleration
Left Wrist ROM	1.00000					
Right Wrist ROM	0.71868	1.00000				
Left Wrist Peak Velocity	0.85055	0.70110	1.00000			
Right Wrist Peak Velocity	0.57802	0.85055	0.56923	1.00000		
Left Wrist Peak Acceleration	0.58681	0.55165	0.70110	0.33187	1.00000	
Right Wrist Peak Acceleration	0.51209	0.66154	0.46813	0.63956	0.73626	1.00000

n=12

Table IV.57. Correlation Statistics, Fasten Shoe – Elbow Component

Spearman Correlation Coefficients	Left Elbow ROM	Right Elbow ROM	Left Elbow Peak Velocity	Right Elbow Peak Velocity	Left Elbow Peak Acceleration	Right Elbow Peak Acceleration
Left Elbow ROM	1.00000					
Right Elbow ROM	0.39780	1.00000				
Left Elbow Peak Velocity	0.50330	0.56484	1.00000			
Right Elbow Peak Velocity	0.31868	0.80220	0.78022	1.00000		
Left Elbow Peak Acceleration	0.09890	0.08132	0.22637	0.27912	1.00000	
Right Elbow Peak Acceleration	0.08132	0.39780	0.49890	0.73187	0.42418	1.00000

n=12

Table IV.58. Correlation Statistics, Fasten Shoe – Shoulder Component

| Spearman Correlation Coefficients	Left Shoulder ROM	Right Shoulder ROM	Left Shoulder Peak Velocity	Right Shoulder Peak Velocity	Left Shoulder Peak Acceleration	Right Shoulder Peak Acceleration
Left Shoulder ROM	1.00000					
Right Shoulder ROM	0.34505	1.00000				
Left Shoulder Peak Velocity	0.51099	0.58791	1.00000			
Right Shoulder Peak Velocity	0.47692	0.81538	0.64286	1.00000		
Left Shoulder Peak Acceleration	0.64286	0.21429	0.88112	0.39560	1.00000	
Right Shoulder Peak Acceleration	0.72527	0.42857	0.43357	0.65385	0.57692	1.00000

n=12
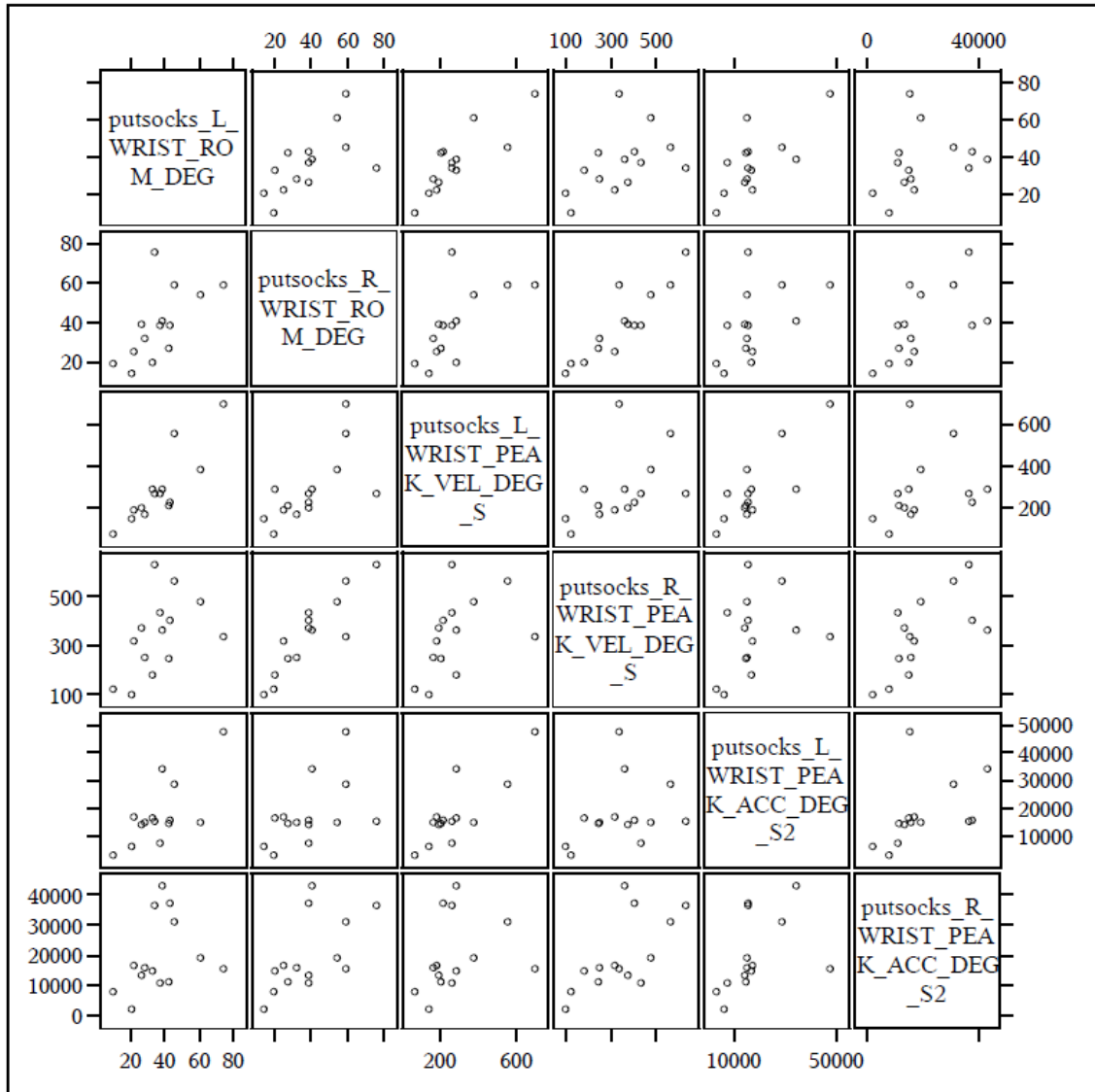
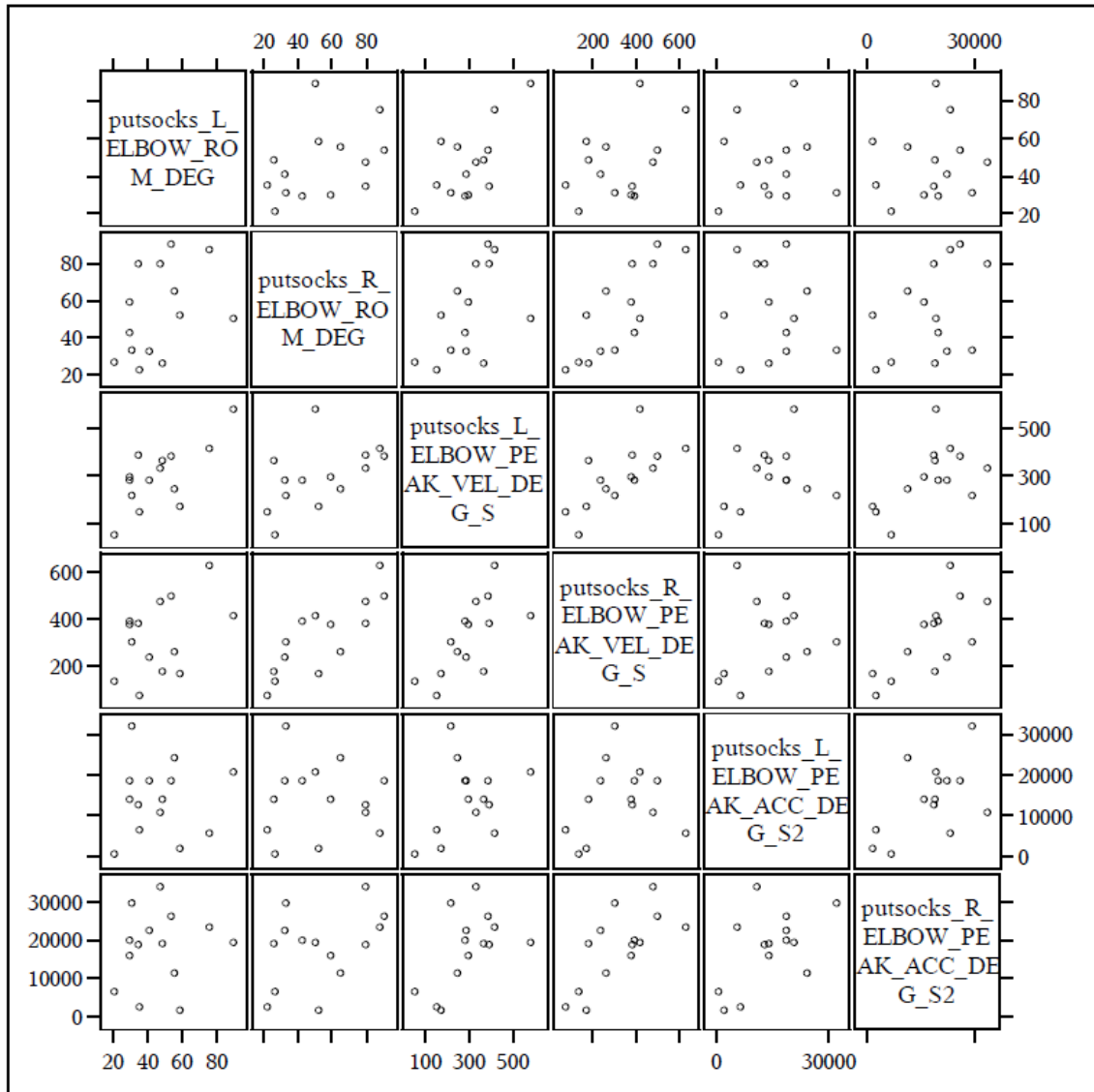*Figure IV.56*. Correlation Plot for Normal Population, Fasten Shoe, Wrist Component

Figure IV.57. Correlation Plot for Normal Population, Fasten Shoe, Elbow Component
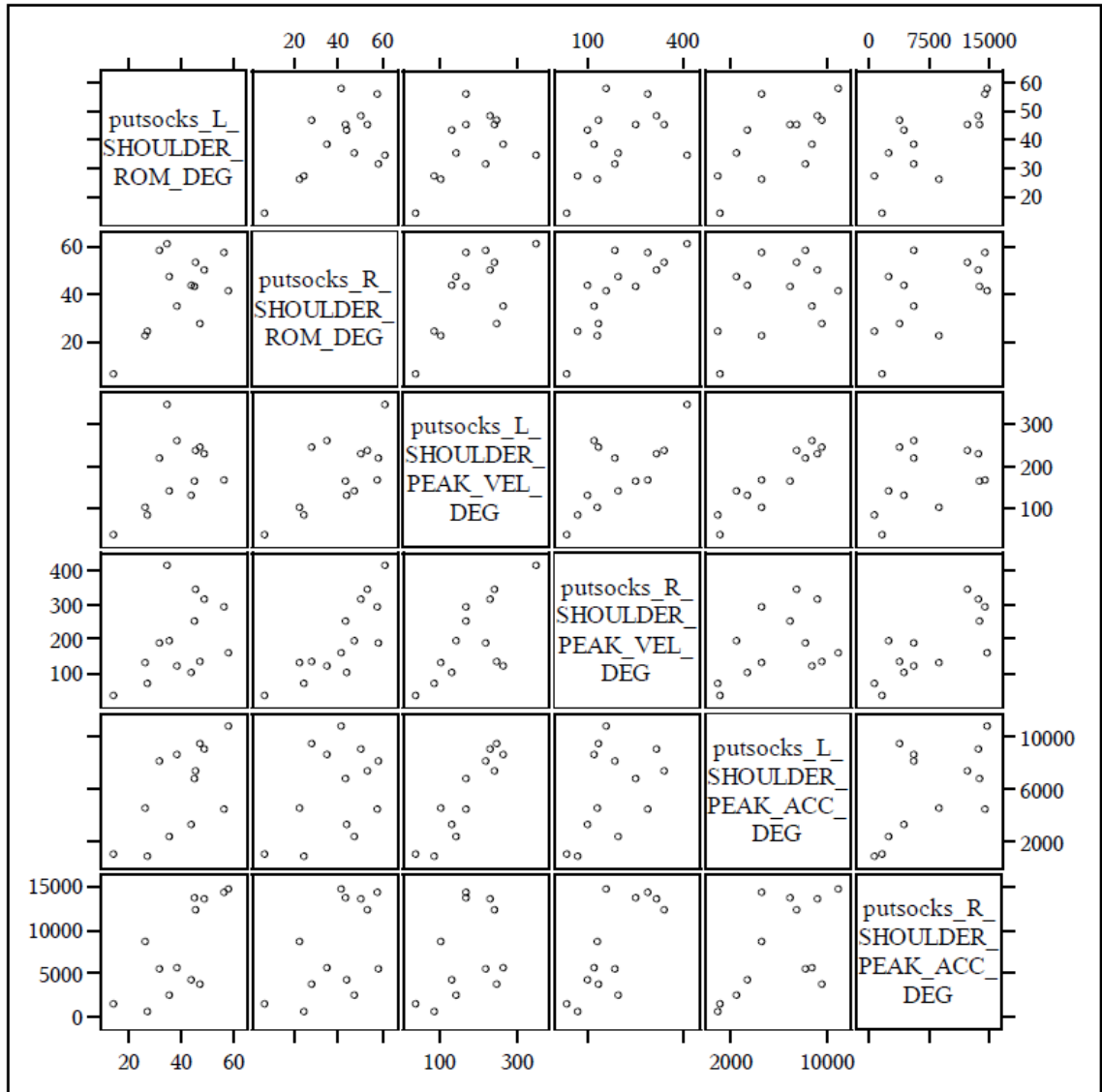
Figure IV.58. Correlation Plot for Normal Population, Fasten Shoe, Shoulder Component