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KINEMATIC AND KINETIC COMPARISONS OF ARM AND HAND REACHING MOVEMENTS WITH MILD AND MODERATE GRAVITY-SUPPORTED, COMPUTER-ENHANCED ARMEO®SPRING: A CASE STUDY

by

Qussai M. Obiedat

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Occupational Therapy

at

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May 2013

ABSTRACT

KINEMATIC AND KINETIC COMPARISONS OF ARM AND HAND REACHING MOVEMENTS WITH MILD AND MODERATE GRAVITY-SUPPORTED, COMPUTER-ENHANCED ARMEO®SPRING: A CASE STUDY

by

Qussai M. Obiedat

The University of Wisconsin-Milwaukee, 2013
Under the Supervision of Professor Ying-Chih Wang

Background: Stroke has been recognized as a leading cause of serious long-term disability in the United States (U.S.) with 795,000 people experience a new or recurrent stroke each year (Roger et al., 2011). The most apparent defect after stroke is motor impairments (Masiero, Armani, & Rosati, 2011). Statistically, half of stroke survivors suffer from upper extremity hemiparesis and approximately one quarter become dependent in activities of daily living (Sanchez et al., 2006). There is strong evidence that intensity and task specificity are the main drivers in an effective treatment program after stroke. In addition, this training should be repetitive, functional, meaningful, and challenging for a patient (Van Peppen et al., 2004). The use of robotic systems to complement standard poststroke multidisciplinary programs is a recent approach that looks very promising. Robotic devices can provide high-intensity, repetitive, task-specific, interactive treatment of the impaired limb and can monitor patients' motor progress objectively and reliably, measuring changes in quantitative movement kinematics and forces (Masiero, Armani, & Rosati, 2011).

Objective: The purpose of this study was to examine the role of Armeo®Spring (Hocoma, Inc.), a gravity-supported, computer-enhanced robotic devise, on reaching movements while using two different gravity-support levels (mild and moderate weight support) on individuals with stroke.

Methods: One stroke subject and one gender-matched healthy control participated in this study after gaining their informed consent. Both subjects performed a computer-based game (picking apples successfully and placing them in a shopping cart) under two gravity weight-support conditions (mild and moderate) provided by the Armeo®Spring device. The game tasks were described as a reaching cycle which consisted of five phases (initiation, reaching, grasping, transporting, and releasing). Joint angles for the glenohumeral and elbow joints throughout the reaching cycle were found. Three kinematic parameters (completion time, moving velocity, acceleration) and one kinetic parameter (vertical force acting on the forearm) was calculated for various instances and phases of the reaching motion. In addition, the muscle activation patterns for anterior deltoid, middle deltoid, biceps, triceps, extensor digitorum, flexor digitorum, and brachioradialis were found and the mean magnitude of the electromyography (EMG) signal during each phase of the reaching cycle was found as a percentage of the subject's maximum voluntary contraction (MVC).

Results: Within the healthy control subject, results demonstrated no significant differences in mean completion time, moving velocity, or acceleration between mild to moderate gravity-support levels during all phases of the cycle. The stroke subject results revealed a significant decrease in the cycle mean completion time ($p= 0.042$) between the two gravity-support levels, specifically in mean completion time of the grasping phase. A significant increase was found in the initiation phase moving velocity ($p=0.039$) and a significant decrease was found in the grasping phase ($p=0.048$) between two gravity-support levels in the stroke subject. Between subjects, significant increase in the cycle mean completion time was found under both mild and moderate conditions ($p<.001$ for both conditions). Additionally, significant decreases in the moving velocities were found in all phases of the cycle between the healthy control and the stroke subject under both conditions. With increasing weight support, the healthy control subject showed an increase in abduction and flexion degrees at the glenohumeral joint level, and an increase in flexion degrees of the elbow joint. On the other hand, the stroke subject showed a decrease in abduction degrees and an increase in flexion degrees at the glenohumeral joint level, and a decrease in flexion degrees of the elbow joint after increasing the weight-support level. Results demonstrated an increase in the mean of vertical forces when changing gravity-support levels from mild to moderate during all phases of the cycle in both stroke and healthy subjects. Last, the average EMG magnitude during the reaching cycle phases was reduced for muscles acting against gravity (anterior deltoid, middle deltoid, biceps, and brachioradialis) in both the healthy control and the stroke subject.

Conclusion: The significant differences in movement performance between mild and moderate physical weight support suggested a preliminary result that the gravity-supported mechanism provides a mean to facilitate functional upper limb motor performance in individuals with stroke. Future studies should examine such effects with larger sample sizes.

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Introduction

Recently, stroke has been recognized as one of the leading causes of serious long-term disability in the United States (U.S.). Approximately 795,000 people experience a new or recurrent stroke each year (Roger et al., 2011). Although the medical treatment improvements of the complications caused by stroke decreased the mortality rate of the disease, 90% of the survivors still suffer from significant neurological deficits (Volpe, Krebs, & Hogan, 2001). The most common defects after stroke are upper extremity functional impairments and disability in activities of daily living (Masiero, Armani, & Rosati, 2011). Statistically, half of stroke survivors suffer from upper extremity impairments and approximately one quarter become dependent in activities of daily living (Sanchez et al., 2006).

Loureiro, Harwin, Nagai, and Johnson (2011) categorized current, available upper extremity stroke rehabilitation methodologies and technologies as: conventional physical and occupational therapy, constraint-induced movement therapy, and robotic-aided and sensor-based therapy systems. Although an increased effort has been made to enhance the recovery process following stroke, patients generally do not reach their full recovery potential when discharged from hospital following initial rehabilitation. This can be attributed to the economic pressure and the lack of available human resources (Loureiro, Harwin, Nagai, & Johnson, 2011). These facts lead to focus more on robot-assisted therapy as an equivalent in quality to traditional methods. The use of robot assisted therapy will deliver therapy at reduced cost and provide a solution to overcome the labor-intensive, one-to-one stroke rehabilitation.

The development, preliminary clinical use, and effectiveness of the Armeo®Spring, a gravity-supported, computer-enhanced robotic devise, for individuals with upper limb motor dysfunction have been supported (Gijbels et al., 2011; Housman, Scott, & Reinkensmeyer, 2009; Sanchez et al., 2006). A study conducted by Sanchez et al., (2006) demonstrated that individuals with chronic stroke whose arm function is compromised in a normal gravity environment could perform reaching and drawing movements while using T-WREX (the prototype version of the Armeo®Spring). The patients improved their motor function (mean change in Fugl-Meyer score was 5 points) over a period of eight weeks. Results from Housman, Scott, & Reinkensmeyer, (2009) showed that, using the T-WREX can improve arm movement ability after chronic severe hemiparesis with brief one-on-one assistance from a therapist (approximately 4 minutes per session). Additionally, the 3-dimensional weight support, instant visual movement feedback, and simple virtual reality software provided by T-WREX were associated with modest sustained gains at 6-month follow-up (mean change in Fugl-Meyer score was 3.6 points) when compared with the conventional approach (mean change in Fugl-Meyer score was 1.5 points). The study conducted by Gijbels et al., (2011) was in multiple sclerosis (MS) and thus results were not described here.

The fundamental kinematic and kinetic comparisons of arm and hand reaching movements with gravity-supported, computer-enhanced Armeo®spring have not been studied. Specifically, how the change of the weight level of support in the Armeo®Spring device may affect the reaching performance of patients with severe stroke. This project aimed to examine the role of the Armeo®Spring on reaching movements while using two different gravity-support levels.

Significance of the Study

Stroke rehabilitation is an important public health issue that needs to be addressed by all health care professionals. It gains this importance because of the increase of the prevalence and incidence of those with stroke disability due to population aging and improved survival after the initial injury (Volpe et al., 2009). Krebs, Volpe, Aisen, & Hogan (2000) described three ways to maximize the productivity in the delivery of rehabilitation without sacrificing the quality of care patients receive. These three methods include: develop evidence-based therapy, re-allocate personnel and tasks, and increase the productivity of each caregiver that can be achieved by providing therapists with appropriate tools.

The increase of the prevalence and incidence of stroke along with the economical pressure and lack of human resources stimulates the interest in the use of robot-assisted techniques to enhance the efficiency and effectiveness of post-stroke rehabilitation (Burgar et al., 2011). On the other hand, it is important to investigate the efficiency of each device and to make sure that it provides realistic clinical expectations as it is supposed to achieve.

Post-stroke rehabilitation has tremendous implication for most of health care professions and stands as an intrinsic part of occupational therapy practice. As "Occupational therapy (OT) aims at facilitating task performance by improving relevant performing skills or developing and teaching compensatory strategies to overcome lost performance skills" (Steultjens et al., 2003). Providing therapists with the proper tools to promote the quality of care provided will play a key role in enhancing occupational therapy interventions and enable therapists to increase their productivity levels.

Background and Literature Review

The World Health Organization (WHO) defines stroke as “a clinical syndrome with rapidly developing clinical signs of focal or global disturbance of cerebral function, lasting more than 24 hours or leading to death with no apparent cause other than of vascular origin.” (Broeks, Lankhorst, Rumping, & Prevo, 1999). It occurs when a blood clot blocks an artery, which is a blood vessel that carries blood from the heart to the body, or when a blood vessel bursts, causing an interruption in the blood flow to an area of the brain. When either of these scenarios happens, brain cells begin to die leading to brain damage (National Stroke Association, 2011). In addition, stroke, or cerebrovascular accident (CVA), can be defined as “a sudden ischemic or hemorrhagic disturbance in the blood supply to brain tissue that results in partial loss of brain function.” (Prange, Jannink, Groothuis-Oudshoorn, Hermens, & Ijzerman, 2006).

Types of Stroke

Stroke has been categorized by the National Stroke Association (2011) according to its underlying cause into two major types: ischemic and hemorrhagic stroke.

Ischemic Stroke. Ischemic stroke accounts for about 87 percent of all cases (American Heart Association, 2011). Naturally, blood clotting is a beneficial physiological process which aims to slow and eventually stop the bleeding from a wound.

However, these clots maybe a source of danger in the case of stroke because they can block arteries and cut off blood flow and oxygen supply to certain areas of the brain, A process which is known as Ischemia (National Stroke Association, 2011).

Ischemic stroke has two subtypes according to the clot formation origin: (a) embolic stroke, (b) thrombotic stroke.

a. Embolic Stroke: the blood clot that causes embolic stroke is formed somewhere in the body, usually the heart, and travels through the bloodstream to the brain. The clot travels in the brain blood vessels until it reaches a small enough vessel to block its passage causing a stroke. The medical word used to describe this type of blood clot is embolus (National Stroke Association, 2011).

b. Thrombotic Stroke: the blood clot causing this type of strokes is formed on a blood vessel causing the blockage to one or more of the arteries supplying blood to the brain. The process leading to this blockage is known as thrombosis referring to the medical description for a clot that forms on a blood-vessel deposit which is thrombus. This blood clot can happen as a result of unhealthy blood vessels clogged with a buildup of fatty deposits and cholesterol. The body reacts regarding these buildups as a multiple, tiny and repeated injuries to the blood vessel wall, as if a bleeding from a wound is present, it responds by forming clots. Two types of thrombosis can cause stroke: large vessel thrombosis and small vessel disease/lacunar infarction (National Stroke Association, 2011).

    i. Large Vessel Thrombosis: large vessel thrombosis is the most common and best understood type of thrombotic stroke. Most of this type of strokes is caused by a combination of long-term atherosclerosis followed by rapid blood clot formation. Patients who have suffered this type of brain attack are more likely to have coronary artery disease, and heart attack is a frequent cause of death (National Stroke Association, 2011).

ii. Small Vessel Disease/Lacunar Infarction: occurs when blood flow is blocked to a very small arterial vessel. Little is known about the causes of small vessel disease, but it is closely linked to high blood pressure or as known as hypertension (National Stroke Association, 2011).

Hemorrhagic Stroke. Hemorrhagic stroke accounts for about 13 percent of stroke cases (American Heart Association, 2011). This type of strokes is caused by the breakage or burst of a blood vessel in the brain. The medical word that describes this type of breakage is hemorrhage which can be caused by a number of disorders that affect the blood vessels, including long-standing high blood pressure and cerebral aneurysms. An aneurysm is defined as a weak or thin spot on a blood vessel wall, which is usually present at birth or develop over a number of years, and usually don't cause detectable problems until they break (National Stroke Association, 2011).

Hemorrhagic stroke is categorized into two subtypes: (a) subarachnoid hemorrhage and (b) intracerebral hemorrhage

a. Subarachnoid hemorrhage (SAH): when an aneurism bursts in a large artery on or near the thin, delicate membrane surrounding the brain, the blood spills into the area around the brain which is filled with a protective fluid, causing the brain to be surrounded by blood-contaminated fluid (National Stroke Association, 2011).

b. Intracerbral hemorrhage: occurs when bleeding from vessels within the brain is present. The primary cause of this type of hemorrhage is hypertension (National Stroke Association, 2011).

Transient Ischemic Attack (TIA). Transient ischemic attack (TIA) is often labeled as a "mini-stroke." It is more accurately characterized as a "warning stroke". Like stroke, TIA is caused by a clot but the only difference between a stroke and TIA is that with TIA the blockage of the blood vessel is transient (temporary). TIA symptoms occur rapidly and last for a relatively short time (less than five minutes; the average is about a minute). Unlike a stroke, when a TIA is over, there's no permanent injury to the brain (National Stroke Association, 2011).

Symptoms & Complications

According to the World Health Organization (WHO) (WHO, 2011) the most common symptom of a stroke is sudden weakness or numbness of the face, arm or leg, mostly on one side of the body. Other symptoms include: confusion, difficulty speaking or understanding speech; difficulty seeing with one or both eyes; difficulty walking, dizziness, loss of balance or coordination; severe headache with no apparent cause; as well as fainting or unconsciousness.

The severity and effects of a stroke depend on where the stroke occurs in the brain (location) and how much the brain is damaged (lesion size) (Volpe, Krebs, & Hogan, 2001; WHO, 2011), resulting in deficits of the cognitive, sensory, affective, and motor functions (Krebs, Volpe, Aisen, & Hogan, 2000).

The most disabling motor deficit following stroke is the loss of arm function. About 85% of stroke survivors have a sensorimotor deficit in the arm which is characterized by muscle weakness, abnormal muscle tone, abnormal movement synergies, lack of mobility between structures at the shoulder girdle, and incoordination during voluntary movement (Cirstea, Ptito, & Levin, 2003). Deficits in the coordinated use of the limb are most evident in the limb contralateral to the damaged side of the brain (Levin, 1996). Attempts to make goal-directed movements with the affected limb in stroke survivors are typically characterized by decreased range of motion (ROM), movement speed, smoothness, coordination, and abnormal pattern of muscle activation (Johnson, Feng, Johnson, & Winters, 2007; Levin, 1996).

The development of upper extremity spastic paresis is a common complication following stroke. It is comprised of positive and negative symptoms that occur to varying degrees in each patient. Positive symptoms include spasticity, hypertonia, increased muscle stiffness, and excessive co-contraction between agonist and antagonist muscles (Leonard, Gardipee, Koontz, Anderson, & Wilkins, 2006). Spasticity is defined as a velocity dependent hyperexcitability of muscles to stretch and is characterized by exaggerated tendon reflexes, increased resistance to passive movement and hypertonia resulting from loss of upper motor neuron inhibitory control (Watkins et al., 2002). Negative symptoms include muscle paresis and discoordination (Leonard, Gardipee, Koontz, Anderson, & Wilkins, 2006). After stroke, spasticity contributes to motor impairments and activity limitations and may become a severe problem for some patients (Sommerfeld, Eek, Svensson, Holmqvist, & von Arbin, 2004). In the upper limb, spasticity may present in two types of synergies. A flexor synergy which consists of forearm supination and elbow flexion combined with shoulder flexion, abduction and external rotation, or extensor synergy which is characterized by forearm pronation and elbow extension associated with shoulder extension, adduction and internal rotation (Levin, 1996).

Motor Recovery

Generally, the largest proportion of the recovery process takes place during the weeks and months that immediately follow stroke occurrence (Volpe, Krebs, & Hogan, 2001). Even though, the rehabilitation process should not be stopped after the acute rehabilitation hospital event. In fact, home training or home training enhanced with devices managed by therapists has the potential to contribute to recovery goals (Volpe, Krebs, & Hogan, 2001).

Motor learning have been defined loosely by motor control scientists by considering it a fuzzy term that encompasses motor adaptation, skill acquisition, and decision making (Huang & Krakauer, 2009). The neuro-rehabilitation science is built up on two basic assumptions, the first one is that motor learning principles apply to motor recovery, and the second assumption is that patients can learn (Huang & Krakauer, 2009).

The recent motor control models suggest that the central nervous system learns a new novel task through practice by constructing a pattern of control variables or making an internal model for that task, and once the new process is earned, it is stored in memory and available for recall (Cirstea, Ptito, & Levin, 2003).

The majority of motor deficit recovery occurs within 6-months post-stroke (Macclellan et al., 2005). According to the available scientific literature, post-stroke rehabilitation intervention is suggested to be significantly more effective when it is delivered in the early phase of recovery. Evidence supports that the better functional outcome is determined by rehabilitation that is initiated promptly and based on intensive multisensory stimulation which is associated with increased adaptive plasticity of the brain in the early post-stroke stages (Masiero, Armani, & Rosati, 2011).

The restoration of motor function in the arm and leg after stroke has been described as an ordered, predictable, stepwise progression by Twitechell (Twitchell, 1951). The initial stage of this progression is flaccid paralysis, after that the development of a basic stereotypical synergy of voluntary movements, and then to normal patterns of voluntary movements. Based on these observations Brunnstrom (Brunnstrom, 1966) divided the progression into 6 sequential stages of motor recovery (Table 1) (Crow & Harmeling-van der Wel, 2008). The early stages are characterized by the appearance of spasticity and the development of stereotypic movement patterns while isolated joint movements are jeopardized. In later stages, spasticity declines and the patient is able to make movements out of synergy. Still later, isolated joint movement and control returns (Levin, 1996).

To understand stroke recovery on a more mechanistic level, two main assumptions are encompassing the recovery process. The first one is that parallel brain regions in the unaffected hemisphere conduct the functions of the contra-lateral hemisphere necrotic tissue by sending its commands via uncrossed pathways. The second assumption is that the adjacent areas of undamaged brain tissue recognize and conduct the functions of the necrotic tissue in the same hemisphere (Krebs, Hogan, Aisen, & Volpe, 1998). The cortical maps reorganization process has been demonstrated in the motor, sensory, auditory, and visual maps. Furthermore, the environment has an influence on the degree of reorganization of the remaining undamaged cortex (as recent animal studies on primates have shown) which suggest that exercising the patients' affected limbs might have a positive effect on neurological restoration of the limb function (Krebs, Hogan, Aisen, & Volpe, 1998).

Table 1. Brunnstrom & Twitechell motor recovery stages (Crow & Harmeling-van der Wel, 2008)

Twitchell	**Brunnstrom**
Flaccid paralysis with areflexia	Stage 1 Flaccid paralysis
Reflex activity returns/spasticity develops	Stage 2 Development of minimal movement in synergies
Voluntary movement in stereotyped flexor and extensor synergies/spasticity is at maximal level	Stage 3 Voluntary movement synergy dependent
Voluntary movement with breaking up of synergies/spasticity is reducing	Stage 4 Some movements out of synergy Stage 5 Movements almost independent of synergy
Normal voluntary movement with normal speed and dexterity/slight hyperactivity of the tendon reflexes	Stage 6 Normal movement with normal speed

Stroke survivors have the tendency to use their unaffected arm in real world tasks (Johnson, Feng, Johnson, & Winters, 2007). Part of the standard treatment for the sensorimotor impairment focus on teaching patients to use the unaffected limb to adapt, compensate, and improve motor abilities with respect to feeding, grooming, and toileting (Volpe et al., 2009). The other emphasis of acute rehabilitation is to teach compensatory rather than restorative methods (Burgar et al., 2011). On the other hand, different studies reported that several approaches, including repetitive passive exercises, forced use of the paretic limb or constraint-induced movement therapy, functional electrical stimulation, increased amounts of therapy including external manipulation, and biofeedback provided positive outcomes on the motor recovery of the affected limb (Krebs, Volpe, Aisen, & Hogan, 2000; Masiero, Armani, & Rosati, 2011).

The literature supports that in order for the therapy to be effective it should contain elements of repetition, intense practice, motivation, and task application. Patient involvement and empowerment along with the use of functional and purposeful tasks in an enriched environment play a key role in increasing patient's motivation and recovery (Wisneski & Johnson, 2007).

The rehabilitation process of the impaired upper limb focuses on reducing impairment and improving independent function on various activities of daily living (ADLs) salient to patients' real life environment. If the patients are able to transfer motor and functional gains achieved during supervised therapy to their daily life this process is considered effective and successful (Johnson, Feng, Johnson, & Winters, 2007).

Robot-assisted Therapy

The use of rehabilitation robots to complement standard post-stroke rehabilitation is a new promising tradition that has been developed intensively in the past few decades (Masiero, Armani, & Rosati, 2011). Examples of upper extremity rehabilitation robots that are currently available in the market or in research labs are Armeo®Spring (Hocoma, Inc), Armeo®Power (Hocoma, Inc), ARMin (Nef, Mihelj, & Riener, 2007), MIT-MANUS (Krebs, Hogan, Aisen, & Volpe, 1998), and T-WREX (Housman, Scott, & Reinkensmeyer, 2009). They have been developed to aid in rehabilitation, alter the physical burden on a therapist to overcome the limited availability of one-to-one stroke rehabilitation, and potentially improve a clinic's productivity (Wagner et al., 2011;

Wang, Wang, Zhang, Wang, & Wang, 2011). Robotic devices can provide repetitive, task-specific, and high-intensity interactive treatment of the impaired limb. They can also measure patients' motor progress objectively and measure changes in movement kinematics and forces (Masiero, Armani, & Rosati, 2011).

A common misperception about robot-assisted therapy is that it would ultimately replace human-administered therapy (Krebs, Volpe, Aisen, & Hogan, 2000). In fact, it is most appropriate to consider the robot as an advanced tool that is used under the therapist supervision to implement relatively simple and labor-intensive therapies (Masiero, Armani, & Rosati, 2011). As the systematic reviews of robot-assisted therapy suggest, these devices met the criteria for improving proximal upper extremity strength and have the potential to promote motor recovery to a greater extent than traditional therapy (Housman, Scott, & Reinkensmeyer, 2009). Individuals who suffer from acute or chronic stroke and receive more therapy with a robotic device can recover more movement ability, and those with chronic stroke who receive matched amounts of robotic and conventional therapy produced comparable therapeutic benefits (Sanchez et al., 2006).

Rehabilitation robots for the upper limb can be classified into passive, active, and interactive systems (Loureiro, Harwin, Nagai, & Johnson, 2011; Riener, Nef, & Colombo, 2005). In passive systems, no actuation is implemented to move patient limbs. Instead, the system constrains the patient's arm to a determined range of motion. They often consist of mechanical linkages that move easily when pushed and their technical components typically include stiff frames, bearings and pulleys, and ropes with counter-weights (Loureiro, Harwin, Nagai, & Johnson, 2011; Riener, Nef, & Colombo, 2005). Active systems are equipped with electromechanical, pneumatic, hydraulic and other drives to move the patient's arm actively through a predefined path. Either the devices are open-loop controlled, or simple position-control strategies are implemented to take a patient's arm from a predefined position to a new position using a certain velocity profile (Loureiro, Harwin, Nagai, & Johnson, 2011; Riener, Nef, & Colombo, 2005). Interactive systems react to the patient's input and characterized not only by actuators but also by sophisticated impedance and other control strategies. They are usually back-drivable and possess low, intrinsic, end point impedance (Loureiro, Harwin, Nagai, & Johnson, 2011; Riener, Nef, & Colombo, 2005).

Gravity Compensation

Little information regarding the effects of gravity compensation on upper limb recovery after stroke was found in the literature. It was reported that stroke patients showed an improved arm function after nine weeks of training using gravity compensation provided by sling suspension, which suggest that the application of gravity compensation may be considered a valuable tool to stimulate functional improvement in stroke rehabilitation (Prange et al., 2009). Another research has shown that gravity compensation in upper limbs decreases the required shoulder abduction torques during two dimensional reaching movements at shoulder height, causing a decrease in coupled elbow flexion leading to an increase in the range of elbow extension (Krabben et al., 2012). Furthermore, the maximal reaching distance during a 3-dimensional movement, starting with the hand at waist height and reaching to a target at shoulder height, is slightly larger when gravity compensation is applied to the arm of stroke patients (Prange et al., 2009).

Reaching Studies

Many studies have examined the reaching movements in stroke (Archambault, Pigeon, Feldman, & Levin, 1999; Cirstea, Ptito, & Levin, 2003; Jannink et al., 2007; Kamper, McKenna-Cole, Kahn, & Reinkensmeyer, 2002; Krabben et al., 2012; Leonard, Gardipee, Koontz, Anderson, & Wilkins, 2006; Levin, 1996; Prange et al., 2009). The analytical variables that have been used to quantify the reaching movements varied among different studies, which included (but not limit to) speed accuracy and efficiency of reaching, peak wrist velocity, endpoint error, reach path ratio, peak speed ratio, number of speed peaks, interjoint coordination, linearity of hand motion, movement direction variability, muscle co-contraction, muscle activation, and trunk compensation. Different analysis methods have been used to determine the movement onsets and offsets. For example, Cirstea and Levin (2000) used the times at which the tangential velocity exceeded or fell below 10% of the peak velocity, while Butler et al. (2010) defined the beginning (i.e., initiation) of each cycle as the first instant when the velocity of the wrist marker exceeded 5% of peak reaching velocity. Kinematic data were low-pass filtered at 5 Hz and 6 Hz (Kamper, McKenna-Cole, Kahn, & Reinkensmeyer, 2002; Wagner, Dromerick, Sahrmann, & Lang, 2007). In general, studies have shown that in stroke subjects multi-joint pointing movements are characterized by decreased movement speed and increased movement variability, by increased movement segmentation and by spatial and temporal incoordination between adjacent arm joints with respect to healthy subjects (Archambault, Pigeon, Feldman, & Levin, 1999; Cirstea & Levin, 2000). Stroke subjects also showed the use of compensatory movement patterns (Cirstea & Levin, 2000). Previous reaching studies available in the literature are illustrated in Appendix.

Specific Aims and Hypothesis

Aim 1: To compare reaching biomechanics between two different gravity-support levels (mild and moderate weight support) in a healthy control using the gravity-supporting exoskeleton apparatus (Armeo®Spring)

Hypothesis 1: We hypothesize that different gravity-support levels do not affect reaching movements in healthy controls.

Aim 2: To compare reaching biomechanics between two different gravity-support levels (mild and moderate weight support) in a stroke subject using the gravity-supporting exoskeleton apparatus (Armeo®Spring)

Hypothesis 2: We hypothesize that the stroke subject will improve the reaching performance under the higher weight support condition. Specifically, we hypothesize that the gravity-supporting facilitates the stroke subject's upper limb movement and thus the stroke subject is able to complete the task more efficiently and with less physical efforts. The moving time would reduce and mean reaching speed would increase.

Aim 3: To compare the biomechanics of reaching movements between a healthy control and a stroke subject using the gravity-supporting exoskeleton apparatus (Armeo®Spring)

Hypothesis 3: We hypothesize that, comparing to the healthy control, the stroke subject would have (a) a longer moving time, (b) slower moving speed, and (c) different muscle activation patterns in the muscles acting against gravity in the upper limb during reaching.

Methods

Participants

This study was conducted at the Gait and Biodynamics Laboratory at the University Services and Research (USR) building on the University of Wisconsin Milwaukee campus. The recruitment process was done through flyers distributed around campus and in the surrounding community and through word-of-mouth. Subjects completed a questionnaire over the phone to determine their eligibility. The study took approximately 2 hours over a one-day course for each participant. Prior to testing, the participants signed an informed consent form to participate in the study per the protocol approved by the University of Wisconsin Milwaukee Institutional Review Board for human subject research.

For the proposed study, one stroke subject and one healthy control were recruited in this study after gaining their informed consent.

Inclusion and exclusion criteria

Qualified participants must be between the age of 18 to 80 for both control and experimental groups. Individuals who have musculoskeletal disorders, sensory disorders, and/or a history of osteoarthritis were excluded from the study. Individuals who do not speak English were not recruited in the study. Individuals who weight over 300 pounds were not included due to the size of the Armeo®Spring device. Women who were pregnant or expecting to be pregnant were not recruited for this study to protect the unborn child and the mother from the risks during testing. Stroke survivors were excluded from the study if they had more than 3 score in the modified Ashworth Scale, onset of stroke is less than 6 months, and/or unstable health conditions in the judgment of the Principal Investigator (PI) and Co-PI would prevent them from participating in this study.

Device: Armeo®Spring

The Armeo®Spring (Figure 1) is a gravity-supporting exoskeleton apparatus that contains no robotic actuators. It is the commercialized product of Therapy Wilmington Robotic Exoskeleton (T-WREX) (Housman, Scott, & Reinkensmeyer, 2009) which has been re-designed by Hocoma, Inc. with user-friendly software and hardware interface to be used in the routine clinical settings. The main structure of the device consists of an arm exoskeleton with integrated springs providing a 5 degree-of-freedom movement at the shoulder, elbow, and wrist levels. It embraces the whole arm, from shoulder to hand, and counterbalances the weight of the patient’s arm providing a sense of arm flotation at all positions in the available workspace. The device level of weight support at the arm and forearm level can be adjusted to provide variable levels of weight support. The length of both the arm and forearm can be adjusted to fit the configuration of the limb and to be used by a wider variety of users. The device has a pressure sensitive handgrip which works as an input device for exercises and can be used as a computer interface for the software and computer games. The handgrip can also be removed for functional training of real life tasks. The device contains built-in sensors which enables it to be used as a 3D input device for computer game playing with the affected arm.

The device comes with computer software (Armeocontrol) which contains an extensive library of game-like movement exercises. The games are designed to mimic functional arm movements, to provide training in a simple virtual reality environment, and to achieve the goal of enabling repetitive task-specific practice.

In all functional exercises, the exercises are mapped into a cubic workspace, which can be adjusted to the movement abilities of each individual. Before starting the exercise session, the workspace has to be defined (i.e., the maximum distance a person can bring his/her hand up, down, left, and right, and how far and close to the body while using the Armeo®Spring) to adjust to the movement abilities of each individual.

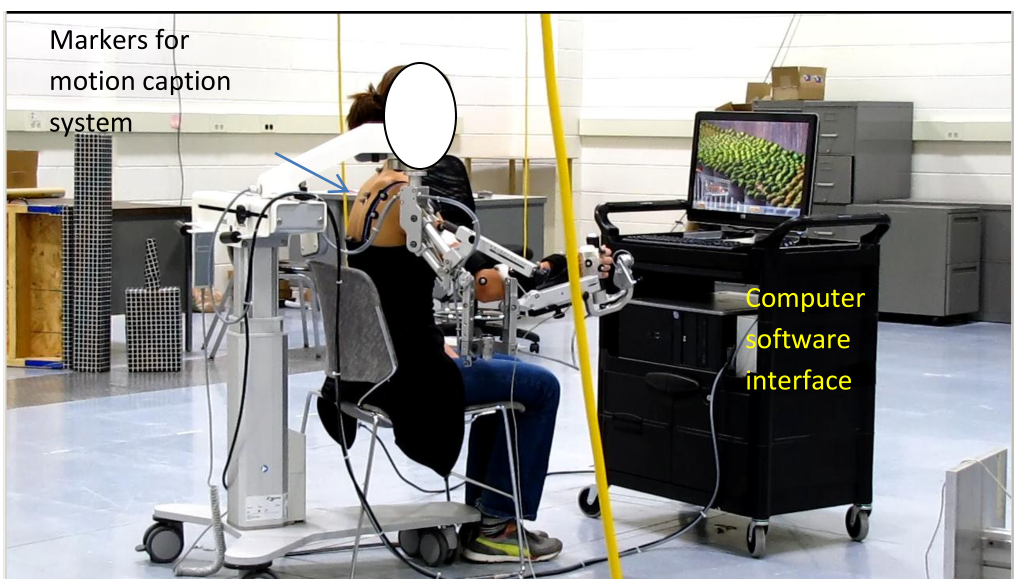

Figure 1. The Armeo®Spring study setup

Armeo®Spring Weight-Support System

The level of weight support is device related (no standardized measuring units have been used to describe level of support) for both arm and forearm (Figure 2). Using the device scale of arm (A-K) and forearm support (1-5), the mild weight-support level was defined as (C – D) support levels and (1 – 2) support levels at the arm and forearm respectively. The moderate weight-support level was defined as (E – G) support levels and (3 – 4) support levels at the arm and forearm respectively. In order to clarify the weight-support system of the device, the differences between variable weight-support levels in both arm and forearm were measured manually using a tension gauge. Results are displayed in table 2.

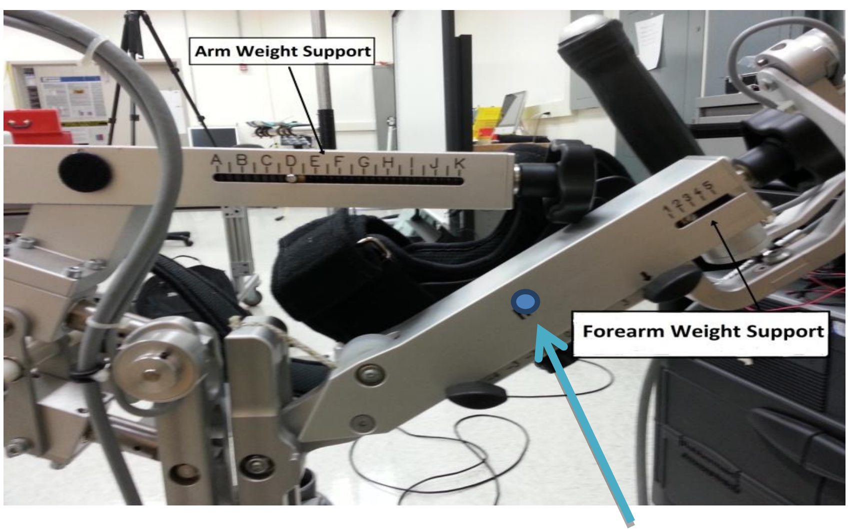

Figure 2. Armeo®Spring weight support system

There is a load cell embedded just underneath the middle of the forearm brace to record the tension force (i.e., vertical supporting force).

Table 2: Armeo®Spring support levels

Body Part	ArmeoSpring Support	Measured Support (N.m)
Arm	**A**	0
	B	0.79
	C	1.65
	D	2.43
	E	3.24
	F	4.01
	G	4.92
	H	5.91
	I	6.91
	J	7.85
	K	8.73
Forearm	**1**	0
	2	0.81
	3	1.63
	4	2.41
	5	3.28

* The moments at the shoulder level were computed for shoulder flexion movement only. The moments at the elbow joint level were computed for elbow flexion movements.

Game: Fruit Shopping

The Fruit Shopping (Figure 3) is one of the games included with Armeocontrol games library. It is about picking apples and placing them in a shopping cart. The apples are green in color and will show up one at a time across a computer screen while the shopping cart is placed at the lower left corner of the screen (for a right-hand user). To complete the game, the user should move a hand-like pointer using the Armeo®Spring from the initial *start* position to *reach* an apple that turns from green to red in color. When the pointer is over the red apple, the user should *squeeze/grasp* the pressure sensitive handgrip of the Armeo®Spring device to hold the apple and *transport* the apple to the shopping cart. When the color of the cart changes the user should take the pressure off the device handgrip to *release* the apple. The phases and tasks of the Fruit Shopping cycle are displayed in Figure 3.

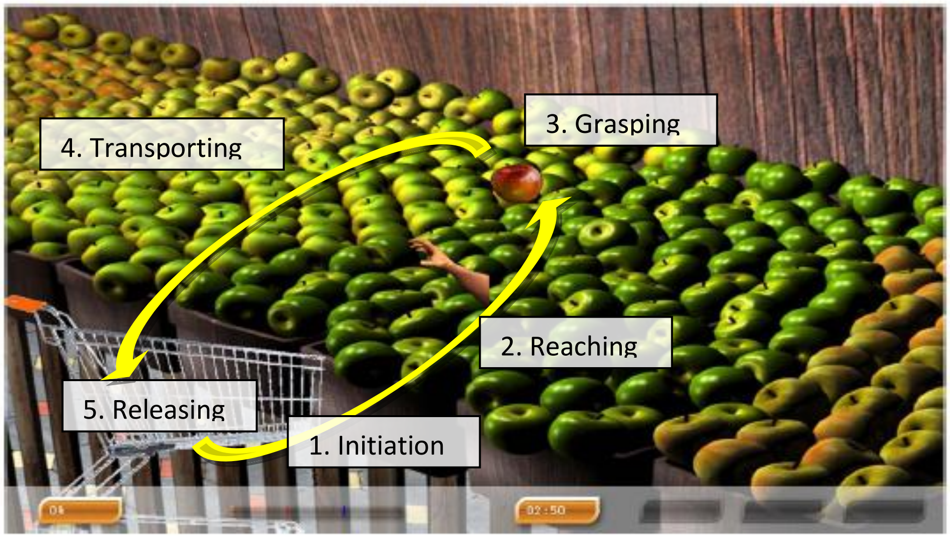

Figure 3. The print screen of the Fruit Shopping game

Data Collection

Three data collection instruments were used for this study to examine the changes that may occur when using the two levels of weight support of the Armeo®Spring device. First, Motion Analysis tracking system (Motion Analysis Corporation, Santa Rosa, CA) was used to record markers (placed on the subject) positions at 100 Hz using 10 infrared, 3-dimentional cameras. Second, muscle activity patterns were measured using surface electromyography (EMG) electrodes using the Trigno ™ 16-channels wireless EMG system (Delsys Inc., Boston, MA). EMG signals were amplified (x1000) and recorded at 1000 Hz sampling rate. The third instrument was a low profile tension and compression load cell (Futek Advanced Sensor Technology Inc., Thomas Irvine, CA) which had been added at the forearm level of the Armeo®Spring device. The load cell collected the vertical forces generated by the limb at 1000 Hz sampling rate.

Procedure

Before data collection, subjects were informed to wear tight fitting clothing on the scheduled data collection date. Upon their arrival, and after signing the informed consent form, clinical assessments including the Fugl Meyer-Upper Arm Scale and the modified Ashworth Scale were administered by the PI to assess the stroke severity of the stroke subject. Afterwards, a total number of 26 reflective markers were placed on the subjects' chests, backs, shoulders, upper arms, and forearms using a double-sided adhesion tape directly to the skin. Marker names and positions are illustrated in Table 3. After that, a total of 7 bipolar surface EMG electrodes were placed to record the activities in the anterior deltoid, middle deltoid, biceps, triceps, extensor digitorum, flexor digitorum, and brachioradialis muscles. Before applying the electrodes, the skin beneath the electrode placing positions was cleaned with alcohol prep pad. Excessive hair, if present, was shaved using a razor. After applying the electrodes, an initial signal check was performed to ensure that the EMG electrodes were functioning. Then, the Maximal Voluntary Contraction (MVC) of each muscle was recorded.

After applying all the markers and EMG electrodes, subjects wore the Armeo®Spring device while sitting on a stationary chair with no arm support. Then, the subjects were instructed to practice the Fruit Shopping game by using Armeo®Spring as an input device for 3-5 minutes. After that, three trials were recorded for each subject while using the Armeo®Spring with mild weight support and three trials with moderate weight support. Within each trial of the Fruit Shopping game, the computer continued to provide the subject an apple for reaching until (a) the end of time (total duration is 3 minutes), or (b) the subject had picked up all the apple (n =17) within the time limit.

Subjects were instructed to rest his/her hand after releasing the apple in the shopping cart for three seconds before reaching another apple at the cart location.

Table 3. Markers used in the motion caption procedure

Abbreviation	Marker name	Abbreviation	Marker name
INJU	Incisura Jugularis	LELB	Lateral epicondyle (Elbow)
STCL	Sternoclaviculare	MELB	Medial epicondyle (Elbow)
XIPH	Processus Xiphoideus	LWRI	Radial styloid (Lateral wrist)
ACRO	Acromioclaviculare	MWRI	Ulnar styloid (Medial wrist)
C7	7th cervical vertebrae	1PHA	Tip of 1st phalanx
T4	4th thoracic vertebrae	2PHA	Tip of 2nd phalanx
TRSC	Trigonum Scapulae	2MCP	2nd Metacarpophalgel
INSC	Angulus Inferior	LHAN	Lower hand
MDSC	dynamic	CHAN	5th MCP
AASC	Angulus Acromialis	S-RU	Superior forearm
S-HU	Superior humerus	I-RU	Lower forearm
I-HU	Lower humerus	FORM	Forearm triangle – medial
FORC	Forearm triangle – central	FORL	Forearm triangle – lateral

MVC Procedure

Subjects were asked to contract each muscle at the highest level they could sustain for ~3 s in duration by pushing up against a research assistant's pushing force. The procedure was repeated three times with a pausing period of 10 s. The greatest value of the trials was recorded as the MVC level. This process was repeated for the seven muscles and each muscle was tested according to the manual muscle testing recommended position. Testing positions are illustrated in table 4.

Kinematic Model

Joint angles were calculated according to the kinematic model proposed by the ISB recommendations on definitions of joint coordinate systems (Wu et al., 2005). The model defined a set of segment coordinate systems and used Euler angles to determine the 3D joint angles. In order to find the glenohumeral joint flexion, abduction/adduction and elbow flexion angles, three segment coordinate systems were defined for the following segments: (1) thorax, (2) right upper arm, and (3) right forearm. The equations used to define the three coordinate systems are illustrated in table 5.

The glenohumeral joint rotation center (GHJC) was estimated by taking 7cm of the vertical offset (Y-direction) of the Acromioclaviculare marker (Schmidt, Disselhorst-Klug, Silny, & Rau, 1999). The elbow joint center was defined as the midpoint between lateral and medial epicondyle (MID_ELB) (Wu et al., 2005).

Due to the nature of the Armeo®Spring device and the experiment setting, some of the markers were obstructed during the trials. In order to overcome this problem two measured coordinate systems were developed to compensate the anatomical coordinate systems of the upper arm and forearm. Two markers were added to the upper arm (S_HU and I_HU) and two markers to the forearm (FORC and FORL) to create the two measured coordinate systems. Also, the marker of the 8th thoracic vertebrae was replaced with a marker on the 4th thoracic vertebrae (T4) as the first marker was obstructed by the backrest of the chair that was used during the experiment.

A static trial was recorded for each subject with all markers (anatomical and measured markers) in order to define two transformation matrices between anatomical and measured coordinate system of the upper arm and forearm. During the experiment trials (dynamic trials) the problematic markers were removed and the measured coordinate systems of the upper arm and forearm were recorded and converted back to the anatomical coordinate systems using the two transformation matrices defined in the static trial.

The angles between coordinate systems were calculated using Euler rotation following ZX’Y’’ sequence. The Z-axis is the flexion/extension axis of the glenohumeral and elbow joints. The X-axis is the abduction/adduction axis of the glenohumeral and elbow joints, and the Y-axis internal/external axis of the upper arm and forearm.

Table 4. MVC testing positions

Muscle	Position
Anterior deltoid	While seated and elbow in slight flexion position, the subject flex their arm to 90° against the resistance force provided above the elbow joint
Middle deltoid	While seated and elbow in slight flexion position, the subject abduct their arm to 90° against the resistance force provided above the elbow joint
Biceps	While seated and with slight shoulder flexion and forearm is supinated, the subject flex elbow to 90° against the resistance force provided above the wrist joint
Triceps	While seated and with slight shoulder flexion and forearm is supinated, the subject extend elbow from 90° of flexion against the resistance force provided above the wrist joint
Extensor digitorum	While forearm resting on a table and pronated, the subject extend their wrist against the resistance force provided at subject’s hand
Flexor digitorum	While forearm resting on a table and supinated, the subject flex their wrist against the resistance force provided at subject’s hand
Brachioradialis	While seated and with slight shoulder flexion and forearm is pronated, the subject flex elbow to 90° against the resistance force provided above the wrist joint

Table 5. Anatomical coordinate systems

Segment	Coordinate System
Thorax	• Origin: GHJC • Yt: ((INJU+C7)/2) – ((XIPH+T4)/2), pointing upward • Zt: cross product of Yt and (C7-INJU), pointing to the right • Xt: cross product of Yt and Zt, pointing forward
Upper arm	• Origin: GHJC • Yh: GHJC – MID_ELB, pointing to GHJC • Zh: cross product of (MWRI - MID_ELB) and Yh, pointing to the right

	• Xh: cross product of Yh and Zh, pointing forward
Forearm	• Origin: MWRI • Yf: MID_ELB – MWRI, pointing proximally • Xf: cross product of Yf and (LWRI – MWRI), pointing forward • Zf: cross product of Xf and Yf, pointing to the right

Data Analysis

The data collected using motion capture system, the load cell, and Trigno ™ wireless EMG system were processed and labeled using Cortex 2.4.0 motion analysis software. The motion analysis data were low-pass filtered at 12 Hz using a Butterworth filter (Butler et al., 2010). Joint angles for three primary motions of the arm: glenohumeral joint flexion-extension, abduction-adduction and elbow flexion–extension were calculated using Matlab (MathWorks, Natick, MA). Each EMG sensor is equipped with band-pass filter with cut-off frequencies 20- 450 Hz. The EMG signal was full-wave rectified and smoothed using Root Mean Square (RMS) function using 0.3 seconds time window (Stoeckmann, Sullivan, & Scheidt, 2009). The muscle activations were measured as percentages of the MVC value.

The Fruit Shopping cycle consisted of five phases: (1) initiation, (2) reaching, (3) grasping, (4) transporting, and (5) releasing & resting. The cycle phases were defined based on the 2MCP marker (base of the index finger on the dorsal side of the hand) coordinates and velocity. The resting periods between the cycles were used to initially segregate the cycles. The beginning (i.e., initiation) of each cycle was identified as the first instant when the velocity of the 2MCP marker exceeded 5% of peak reaching velocity and continued to increase until it reached 30% of peak reaching velocity while the 2MCP marker coordinates increased in two axes at least (Butler et al., 2010). The reaching phase started when the peak reaching velocity exceeded 30% and continued until 2MCP marker reach back to 5% of its peak reaching velocity. The grasping phase started when the 2MCP marker reached 5% of its peak velocity after the reaching phase and ended when the 2MCP marker reach back to the last 5% of its peak velocity before reaching to 30% again. The transporting phase started when the velocity of 2MCP marker exceeded 5% of its peak velocity following grasping phase and ended when the 2MCP marker reached back to 5% of its peak velocity. Then, the end of the cycle was signified by a decrease in 2MCP marker velocity to less than 5% of the peak velocity upon returning the arm to the initial position.

For each phase, three kinematic parameters (completion time, moving velocity, acceleration) and one kinetic parameter (arm vertical supporting force) were calculated. Velocity and acceleration parameters were computed based on the 2MCP marker using the 3-point central difference method. In addition, the average magnitude of the EMG envelope was calculated for each phase. For visual inspection purpose, we plotted the joint angles during one reaching cycle and compared the changes under mild and moderate weight support conditions.

Independent t-test was used to compare between-group differences (stroke subjects vs. healthy controls). Sample t-test was used to compare within group differences (i.e., data from the same stroke subject or data from the same healthy control).

Results

Two subjects were recruited for this case study. A healthy control subject (female, 35 years, 110 lb, 1.52m, right side dominant) and a stroke subject (female, 54 years, 110 lb, 1.47m, right side dominant). The stroke subject had a stroke for 18 months in her right side with a Fugl-meyer score of 27/66. Descriptions of subjects' mild and moderate weight-support levels provided by the Armeo®Spring device are illustrated in table 6.

Table 6. Armeo®Spring mild and moderate weight-support levels for stroke and healthy subjects.

Subject	Body Part	Level of Support		Support Difference (N.m)
		Mild	Moderate	
Healthy	Arm	D	G	1.58
	Forearm	2	4	1.63
Stroke	Arm	C	E	2.50
	Forearm	1	3	1.61

* Different baseline support (i.e., mild weight support) was adjusted accordingly depending on the weight of the subject's arm, such that with the mild weight support provided by the Armeo®Spring the subject's hand was floating just above the knee height in a sitting position. With the moderate weight support, which was increased with 2 to 3 units weight support (e.g., from C to E was a 2-level increase), the subject's arm was floating near the theoretic but not exceeding the shoulder height.

Kinematic parameters

The first two research hypotheses pertained to the within group differences in reaching performance. As hypothesized within the healthy control subject, results demonstrated no significant differences in mean completion time, moving velocity, or acceleration between mild to moderate gravity-support levels during all phases of the cycle (Table 7). As predicted within the stroke subject (Table 8), results revealed a significant decrease in the cycle mean completion time ($p= 0.042$). Specifically, a significant decrease was found in mean completion time of the grasping phase ($p=0.043$) between the two gravity-support levels (Figure 4). When comparing the moving velocity within the stroke subject, a significant increase was found in the initiation phase moving velocity ($p=0.039$) and a significant decrease was found in the grasping phase ($p=0.048$)

between two gravity-support levels. No significant differences were found in all phases of the cycle when comparing the movement acceleration between the two gravity-support levels.

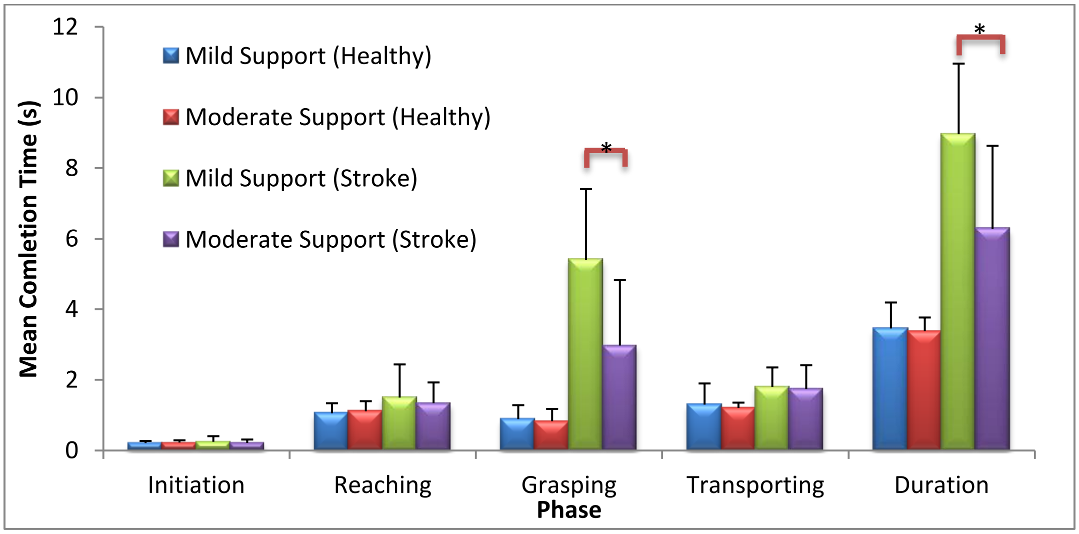

Figure 4. Mean completion time between the two gravity-support levels

Table 7. Kinematic parameters of the healthy subject with mild & moderate weight support

Support Level	Parameter		Phase				
			Initiation	Reaching	Grasping	Transporting	Cycle
Mild	Completion Time	Mean (s)	0.21	1.05	0.89	1.30	3.46
		SD	0.06	0.28	0.39	0.60	0.74
	Velocity	Mean (mm/s)	85.97	220.24	30.38	198.64	153.76
		SD	5.13	29.02	7.89	20.72	26.73
	Acceleration	Mean (mm/s^2)	577.10	-127.63	4.88	-2.18	-1.51
		SD	64.36	18.40	3.66	1.96	2.75
Moderate	Completion Time	Mean (s)	0.23	1.11	0.83	1.21	3.38
		SD	0.06	0.29	0.35	0.15	0.39
	Velocity	Mean (mm/s)	87.30	222.03	29.96	195.88	145.95
		SD	8.30	18.14	5.85	22.19	26.14
	Acceleration	Mean (mm/s^2)	556.46	-120.61	3.70	-2.69	-1.50
		SD	58.83	23.89	3.89	2.71	2.82

Table 8. Kinematic parameters of the stroke subject with mild & moderate weight support

Support Level	Parameter		Phase: Initiation	Reaching	Grasping	Transporting	Cycle
Mild	Completion Time	Mean (s)	0.25	1.50	5.41	1.81	8.96
		SD	0.16	0.95	5.60	0.49	6.06
	Velocity	Mean (mm/s)	50.47	124.80	54.50	90.49	77.10
		SD	5.84	28.97	14.71	26.84	17.36
	Acceleration	Mean (mm/s^2)	441.88	-68.59	-0.15	0.52	0.38
		SD	263.92	41.05	3.72	3.19	0.84
Moderate	Completion Time	Mean (s)	0.22	1.34	2.98	1.75	6.28
		SD	0.10	0.59	1.86	0.67	2.35
	Velocity	Mean (mm/s)	54.46	130.33	46.09	96.28	79.94
		SD	8.33	34.13	16.71	28.62	18.28
	Acceleration	Mean (mm/s^2)	442.27	-73.03	-1.78	1.90	0.20
		SD	191.04	37.50	7.03	7.69	1.04

The final hypothesis pertained to between groups reaching performance differences. As hypothesized, differences between the healthy control and the stroke subject revealed a significant increase in the cycle mean completion time ($p<.001$) while using mild gravity-support level. While using moderate gravity-support level, a significant increase ($p<.001$) in the mean completion time was found between subjects, specifically, significant increases in the mean completion time were found in all phases of the cycle except the initiation phase. Also, significant decreases in the moving velocities were found in all phases of the cycle between the healthy control and the stroke subject under both conditions.

Joint Angles

After increasing the weight-support provided by the Armeo®Spring device, the healthy control subject showed an increase in abduction and flexion degrees at the glenohumeral joint level, and an increase in flexion degrees of the elbow joint. On the other hand, the stroke subject showed a decrease in abduction degrees and an increase in flexion degrees at the glenohumeral joint level, and a decrease in flexion degrees of the elbow joint after increasing the weight-support level. Figure 5 displays the average joint angles during the reaching cycle for the healthy subject (upper panel) and the stroke subject (lower panel).

Forearm Vertical Forces

Results demonstrated an increase in the mean of vertical forces when changing gravity-support levels from mild to moderate during all phases of the cycle in both stroke and healthy subjects. Differences between the healthy control and the stroke subject revealed an increase in the cycle mean of vertical forces (1.78 lbs) while using mild gravity-support level. While using moderate gravity-support level, an increase in the cycle mean of vertical forces (2.67 lbs) was found between subjects. The average vertical forces for the two subjects during each phase of the reaching cycle are illustrated in table 9 for both weight-support levels.

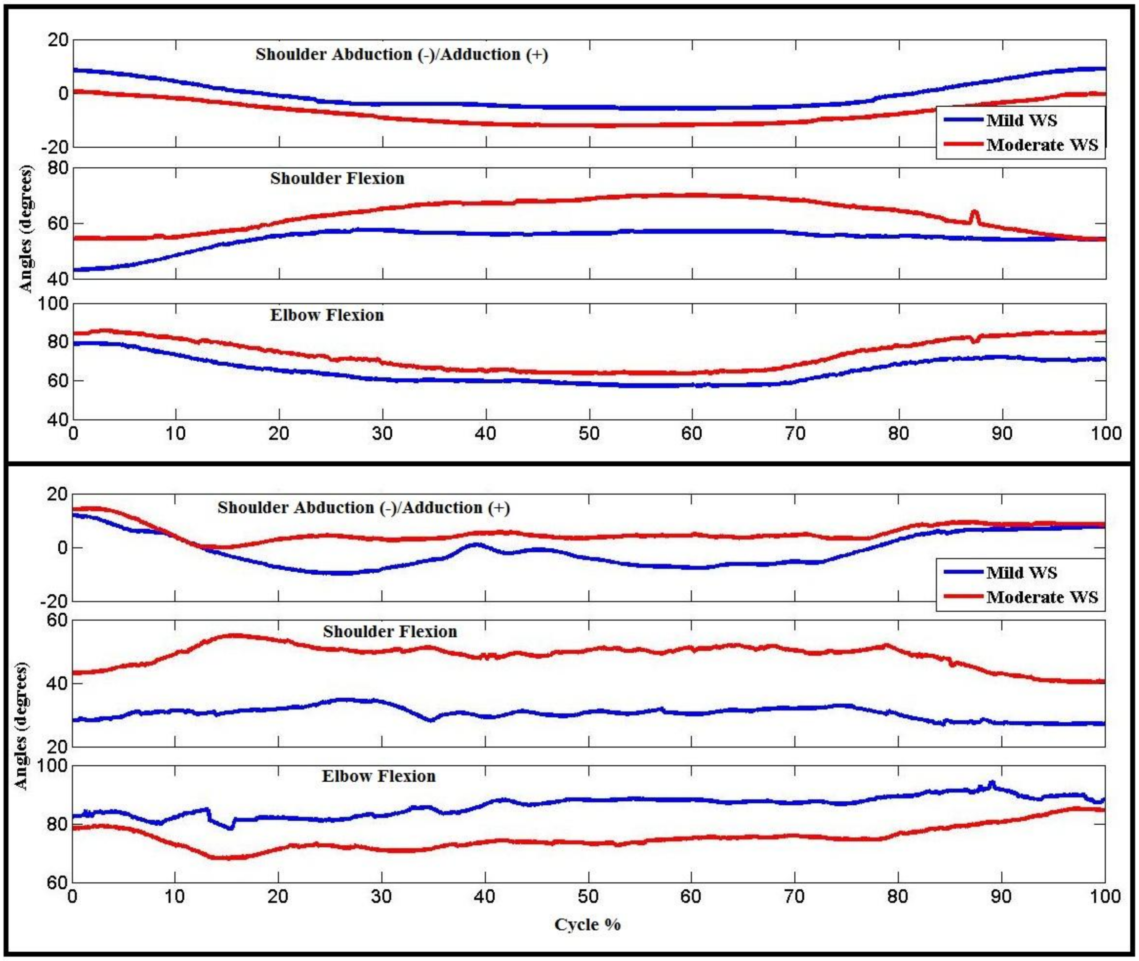

Figure 5. Joint angle changes during the reaching cycle for the healthy subject (upper panel) and the stroke subject (lower panel).

* 0 degree in shoulder abduction/adduction means that the upper arm is located at the side of the body with no abduction or adduction, the positive increase in the angles indicate shoulder adduction and the negative increase indicates shoulder abduction . 0 degree in shoulder flexion means that the arm is located at the side of the body with no anterior flexion. 0 degree in elbow flexion means that the forearm is fully extended.

Electromyography (EMG)

Within the healthy control subject, EMG muscle activation patterns were the same for all the muscle between mild and moderate gravity-support level. The average EMG magnitude for anterior deltoid, middle deltoid, biceps, and brachioradialis were significantly decreased during all the phases of the reaching cycle ($p<.001$ for all muscles) when changing the weight-support level from mild to moderate support. Furthermore, no significant difference was found in the average EMG magnitude for the triceps, extensor digitorum, and flexor digitorum muscles during all phases of the reaching cycle between the two weight-support levels. Table 10 displays the average EMG magnitude between two support levels for the healthy control subject.

Within the stroke subject, the average EMG magnitude for the anterior deltoid, biceps, and brachioradialis muscles were significantly decreased in all phases of the reaching cycle when changing weight-support level from mild to moderate support. On the other hand, the average EMG magnitude of the triceps muscle was significantly increased in all phases of the cycle ($p<0.001$ during initiation, $p=0.001$ during reaching, $p=0.005$ during grasping, and $p<0.001$ during transporting). No significant difference was found in the middle deltoid muscle average EMG magnitude during the phases of the cycle except a significant decrease in the reaching phase ($p=0.006$) between two weight-support levels. Furthermore, no significant difference was found in the average EMG magnitude for the extensor digitorum and flexor digitorum muscles during all phases of the reaching cycle between the two weight-support levels. Table 11 displays the average EMG magnitude between two support levels for the stroke subject.

When comparing two subjects under the two weight-support conditions, the results revealed significant decrease in the average EMG magnitude for all muscles during all phases of the reaching cycle except for the anterior deltoid muscle. Under the mild weight-support condition, no significant difference was found in the average EMG magnitude during the initiation, grasping, and transporting phases. Under the moderate weight-support, no significant difference was found during the grasping and transporting phases. P-values for between-subjects average EMG magnitude are illustrated in table 16.

Table 9. Vertical support forces for healthy control and stroke subject with mild & moderate weight support

Subject	Support Level	Vertical Force	Phase			
			Initiation	Reaching	Grasping	Transporting
Healthy	Mild	Mean (lb)	4.73	2.18	1.43	5.10
		SD	0.32	0.58	0.43	0.57
	Moderate	Mean (lb)	7.39	5.03	4.72	7.38
		SD	0.42	0.51	0.64	0.43
Stroke	Mild	Mean (lb)	7.20	5.99	6.14	6.89
		SD	0.43	0.15	0.68	0.85
	Moderate	Mean (lb)	8.44	7.78	7.59	8.25
		SD	0.63	0.46	0.36	0.33

Table 10. Healthy subject EMG average magnitude (% of MVC)

Level of support	Phase	EMG	Ant. Deltoid	Mid. Deltoid	Biceps	Triceps	Ext. Digitorum	Flex. Digitorum	Brachioradials
Mild Support	Initiation	Mean	15.40	7.82	2.75	2.27	3.86	0.92	1.97
		SD	1.96	1.20	0.72	0.14	0.65	0.18	0.39
	Reaching	Mean	21.42	11.73	5.31	2.35	4.68	1.02	2.34
		SD	1.61	1.23	1.20	0.15	0.77	0.18	0.45
	Grasping	Mean	22.08	11.67	6.59	2.52	13.22	3.49	9.62
		SD	3.73	1.83	1.31	0.21	2.60	0.78	2.71
	Transporting	Mean	14.76	6.58	4.52	2.52	11.56	3.52	9.07
		SD	1.61	0.94	1.26	0.32	2.46	0.74	1.90
Moderate Support	Initiation	Mean	9.17	3.97	0.65	2.36	3.64	3.31	1.28
		SD	1.90	0.69	0.29	0.19	0.66	0.15	0.34
	Reaching	Mean	13.79	7.48	1.27	2.37	4.55	1.04	1.40
		SD	1.25	1.11	0.26	0.16	0.56	1.37	0.38
	Grasping	Mean	12.21	6.47	1.51	2.63	12.15	3.26	7.28
		SD	2.07	1.24	0.39	0.29	2.28	0.58	1.55
	Transporting	Mean	5.44	4.57	0.49	2.64	10.70	3.45	6.19
		SD	1.61	0.92	0.11	0.13	1.46	1.06	0.82

Table 11. Stroke subject EMG average magnitude (% of MVC)

Level of support	Phase	EMG	Ant. Deltoid	Mid. Deltoid	Biceps	Triceps	Ext. Digitorum	Flex. Digitorum	Brachioradials
Mild Support	Initiation	Mean	15.66	12.33	68.77	15.03	18.07	16.71	26.27
		SD	5.79	2.79	23.06	3.60	6.35	3.21	7.74
	Reaching	Mean	33.27	18.89	79.06	15.82	28.31	21.71	45.78
		SD	14.67	5.90	18.28	3.82	7.13	4.25	9.71
	Grasping	Mean	30.12	21.76	87.02	24.69	43.50	39.50	76.13
		SD	16.08	10.33	8.94	12.21	5.16	7.92	6.53
	Transporting	Mean	11.01	10.54	84.08	27.55	33.50	41.58	59.97
		SD	5.56	4.25	10.91	6.86	5.19	7.78	6.66
Moderate Support	Initiation	Mean	6.41	10.38	22.28	35.97	19.86	18.04	16.25
		SD	1.51	5.19	11.40	7.49	18.40	11.22	8.69
	Reaching	Mean	8.03	11.64	30.96	31.53	21.70	19.91	23.81
		SD	2.08	2.47	9.53	8.68	14.26	9.45	10.12
	Grasping	Mean	10.14	14.48	44.25	40.52	40.08	34.10	49.89
		SD	3.00	0.96	13.26	6.78	9.42	7.27	9.70
	Transporting	Mean	6.69	11.71	46.29	61.07	30.08	42.18	37.20
		SD	1.60	1.98	12.88	9.25	4.95	4.47	2.94

Table 12. Healthy subject EMG minimum magnitude (% of MVC)

Level of support	Phase	EMG	Ant. Deltoid	Mid. Deltoid	Biceps	Triceps	Ext. Digitorum	Flex. Digitorum	Brachioradials
Mild Support	Initiation	Mean	13.30	6.24	1.90	2.18	2.91	0.78	1.54
		SD	2.51	1.57	0.86	0.12	0.80	0.19	0.37
	Reaching	Mean	16.62	8.96	3.47	2.12	3.58	0.80	1.81
		SD	1.77	1.00	0.73	0.06	0.89	0.15	0.39
	Grasping	Mean	17.75	8.89	5.13	2.23	5.96	1.26	2.95
		SD	2.87	1.09	1.06	0.15	1.06	0.26	0.73
	Transporting	Mean	11.45	4.42	2.93	2.10	7.64	2.26	6.06
		SD	1.57	0.74	1.40	0.11	2.96	0.86	2.64
Moderate Support	Initiation	Mean	7.10	3.04	0.50	2.48	1.68	0.60	1.15
		SD	2.02	0.69	0.27	0.18	0.61	0.07	0.30
	Reaching	Mean	10.61	4.67	0.74	2.20	1.39	0.56	0.97
		SD	1.73	0.87	0.23	0.08	0.77	0.08	0.33
	Grasping	Mean	9.28	5.10	1.18	2.28	3.66	1.02	2.28
		SD	2.20	1.19	0.36	0.22	1.49	0.41	1.13
	Transporting	Mean	2.19	2.54	0.25	2.22	5.10	1.53	4.09
		SD	0.76	1.05	0.01	0.23	1.50	0.38	1.27

Table 13. Stroke subject EMG minimum magnitude (% of MVC)

Level of support	Phase	EMG	Ant. Deltoid	Mid. Deltoid	Biceps	Triceps	Ext. Digitorum	Flex. Digitorum	Brachioradials
Mild Support	Initiation	Mean	11.42	8.88	62.62	13.61	15.92	14.71	23.91
		SD	6.60	3.71	22.30	2.77	5.89	3.35	7.24
	Reaching	Mean	16.26	10.84	54.71	12.15	17.31	14.73	23.93
		SD	9.44	4.56	22.61	0.99	6.21	3.25	7.99
	Grasping	Mean	15.67	9.67	58.85	12.85	30.23	22.51	45.41
		SD	13.08	6.09	10.59	1.39	7.91	4.77	10.88
	Transporting	Mean	4.03	5.06	55.07	13.86	14.31	30.63	33.09
		SD	0.27	0.93	12.86	3.07	5.93	5.37	8.03
Moderate Support	Initiation	Mean	5.77	9.18	18.84	31.61	17.62	15.54	14.80
		SD	1.62	4.97	11.16	8.76	16.92	9.56	7.03
	Reaching	Mean	4.64	5.70	16.00	15.27	12.25	12.41	13.73
		SD	1.30	1.40	5.17	3.03	9.87	4.00	4.42
	Grasping	Mean	4.42	6.22	25.80	16.96	13.94	14.52	18.56
		SD	0.73	1.22	9.92	4.97	7.86	3.75	5.87
	Transporting	Mean	4.37	6.43	30.55	35.39	6.42	33.82	22.47
		SD	0.46	1.75	11.17	10.37	0.68	4.98	4.11

Table 14. Healthy subject EMG maximum magnitude (% of MVC)

Level of support	Phase	EMG	Ant. Deltoid	Mid. Deltoid	Biceps	Triceps	Ext. Digitorum	Flex. Digitorum	Brachioradials
Mild Support	Initiation	Mean	17.33	9.31	3.57	2.36	4.61	1.05	2.31
		SD	1.84	1.12	0.74	0.16	0.57	0.17	0.40
	Reaching	Mean	25.37	13.92	7.18	2.60	6.34	1.38	3.28
		SD	2.06	1.48	1.85	0.38	0.96	0.28	0.68
	Grasping	Mean	26.26	14.26	8.10	2.87	21.72	6.02	17.80
		SD	4.88	3.01	1.82	0.36	4.48	1.19	3.98
	Transporting	Mean	19.18	9.54	7.11	2.88	17.61	5.05	14.36
		SD	2.69	1.37	1.38	0.51	3.29	0.96	2.97
Moderate Support	Initiation	Mean	10.96	4.84	0.84	2.84	2.30	0.70	1.40
		SD	1.83	0.87	0.30	0.18	0.71	0.10	0.37
	Reaching	Mean	15.77	9.33	1.82	2.83	3.99	1.09	2.48
		SD	1.29	1.48	0.41	0.33	1.29	0.36	1.01
	Grasping	Mean	14.57	7.98	1.83	2.98	13.18	4.24	11.89
		SD	2.57	1.46	0.47	0.46	1.49	0.49	1.58
	Transporting	Mean	9.89	6.38	1.55	3.31	10.90	3.38	9.77
		SD	2.15	1.28	0.47	0.26	1.38	0.54	1.39

Table 15. Stroke subject EMG maximum magnitude (% of MVC)

Level of support	Phase	EMG	Ant. Deltoid	Mid. Deltoid	Biceps	Triceps	Ext. Digitorum	Flex. Digitorum	Brachioradials
Mild Support	Initiation	Mean	20.16	15.78	76.14	17.03	20.45	18.74	28.54
		SD	7.02	3.61	25.70	5.24	6.30	3.69	8.17
	Reaching	Mean	50.69	27.56	98.77	21.69	40.22	30.28	76.48
		SD	19.24	8.06	15.70	9.38	10.41	6.14	11.18
	Grasping	Mean	54.77	38.14	118.98	54.79	79.83	60.28	114.43
		SD	21.61	15.67	13.54	29.03	11.16	11.54	14.29
	Transporting	Mean	25.87	19.96	114.10	47.29	66.86	55.60	102.26
		SD	20.00	12.15	13.50	13.91	9.01	10.07	21.16
Moderate Support	Initiation	Mean	6.90	11.33	25.40	40.01	22.24	20.53	17.22
		SD	1.50	5.64	11.62	5.80	20.82	11.77	9.37
	Reaching	Mean	15.13	18.26	47.18	51.06	35.13	29.23	37.16
		SD	7.75	5.92	13.21	14.10	25.56	15.69	27.18
	Grasping	Mean	24.20	32.11	63.03	78.72	73.12	58.44	96.82
		SD	10.02	14.13	16.81	17.89	9.86	13.04	21.45
	Transporting	Mean	12.51	18.18	61.87	86.22	60.53	55.24	73.63
		SD	7.32	5.21	13.89	13.20	14.25	4.96	9.03

Table 16. P-values for between-subjects average EMG magnitude

Level of support	Phase	Ant. Deltoid	Mid. Deltoid	Biceps	Triceps	Ext. Digitorum	Flex. Digitorum	Brachioradials
Mild Support	Initiation	0.899	0.001	0.000	0.000	0.000	0.000	0.000
	Reaching	0.042	0.006	0.000	0.000	0.000	0.000	0.000
	Grasping	0.176	0.019	0.000	0.001	0.000	0.000	0.000
	Transporting	0.080	0.024	0.000	0.000	0.000	0.000	0.000
Moderate Support	Initiation	0.001	0.010	0.001	0.000	0.041	0.008	0.002
	Reaching	0.000	0.002	0.000	0.000	0.011	0.001	0.000
	Grasping	0.110	0.000	0.000	0.000	0.000	0.000	0.000
	Transporting	0.093	0.000	0.000	0.000	0.000	0.000	0.000

Discussion

Our hypothesis was that gravity compensation would influence the movement performance and muscle activation patterns of stroke patients than the healthy controls. Knowledge of the nature and direction of these changes will enhance our understanding of underlying working mechanisms of the influence of gravity compensation on improvements in arm movement ability.

The present case study provided initial experimental data on the effects of increasing gravity weight-support levels on the upper limb reaching movements using a gravity-supported, computer-enhanced Armeo®Spring device in stroke survivors. The results of this study provided evidence that increasing the amount of gravity weight-support provided to the upper limb has a potential to enhance the ability of stroke survivors to perform faster, and more smooth reaching movements.

The data showed that the increase in the gravity weight-support levels enabled the stroke subject to complete the reaching cycle in significantly less time. This significance is attributed to the significant decrease in the time needed to complete the grasping phase of the cycle which means that the increase in gravity weight-support level enabled the subject to perform a more accurate and precise movement to reach for their target (the apple). Also, this can be supported by the significantly decreased moving velocity found during the grasping phase, as lower moving velocity is needed in order to execute more accurate movements. Additionally, the moving velocity during initiation phase of the cycle was significantly increased when changing the weight-support to a higher level. This increase may indicate that the device is capable of helping stroke patient to initiate movements more efficiently which is a barrier that most of stroke survivors face when they attempt to make goal-directed movements. Based on our knowledge, no studies were found reporting the effects of increasing the gravity compensation on the task completion time or the moving velocity of the upper arm.

When comparing muscle activity levels during the cycle between two different support levels, we found that the level of muscle activity was lower during movements with higher weight-support in the anterior deltoid, middle deltoid, biceps, and brachioradialis muscles in both the stroke subject and the control subject. In other words, in both stroke and control subjects, the increase in weight-support level reduced the level of muscle activity needed to hold the arm in a certain orientation during the cycle. These results are consistent with findings reported by Jannink et al. (2007) and Prange et al. (2009). This finding supports that the Armeo®Spring device enable the stroke patients to generate movements with less efforts. Perry, Powell, and Rosen (2009) reported that the majority of human arm joint torques are devoted to supporting the human arm position in space while compensating gravitational loads whereas a minor portion is dedicated to arm motion itself.

During the reaching cycle, the results showed a decrease in the glenohumeral joint abduction movements accompanied with an increase in the elbow joint extension movements in the stroke subject while using a higher weight-support level. These results suggest that the increase in weight-support level changed the motion control mechanism to depend more on the movement of the distal joint (elbow) with less contribution from the proximal joint (glenohumeral) to complete the reaching cycle. This suggestion can explain the increased EMG magnitude found in triceps muscle after increasing the level of weight-support. This finding can be supported by a recent research that showed that the arm support decreases the required shoulder abduction torques during two dimensional reaching movements at shoulder height, subsequently causing a decrease in coupled elbow flexion, leading to an increase in the range of elbow extension (Iwamuro, Cruz, Connelly, Fischer, & Kamper, 2008; Krabben et al., 2012). The increase in the triceps EMG magnitude can be attributed also to force needed to push against the extra weight support provided by the Armeo®Spring device under the moderate weight-support condition.

The stroke subject showed larger shoulder adduction movements comparing to the healthy control, however, these results were difficult to conclude as the moving range (i.e., working space) was calculated and defined for each subject to allow each individual to be able to complete the Fruit Shopping task.

There were several limitations of this study. First, we encountered challenges in study setup as the markers were sometimes obstructed by the Armeo®Spring devices while subjects were performing the reaching task. We have spent considerable amount of time to perform data cleaning (fill in gaps, correct switching maker data) to ensure the quality and validity of the data. Second, we did not randomize the two conditions (mild and moderate weight-support). Subjects were instructed to complete the Fruit Shopping under mild weight support followed by moderate weight support. As a result, one could argue that observed changes under these two conditions might be due to practice or fatigue effects.

In summary, the significant differences in movement performance between mild and moderate physical weight support suggest the gravity-supported mechanism provides a mean to facilitate functional upper limb motor performance in individuals with stroke.

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Appendix A: Previous Reaching Studies in the Literature

AUTHOR (year)	N	AGE (years)	TIME SINCE STROKE	RESEARCH DESIGN	OUTCOME MEASURES	RESULTS & CONCLUSION
Cirstea, Ptito, & Levin **(2003)**	30	right hand-dominant EG: 19 to 74 years (mean ± SD: 53.5±16.4 years) CG: aged 43.3±18.2 years	EG: right hemiparesis due to a single leftsided cerebrovascular accident (CVA) that occurred 3–17 months prior to the study	Figure 1 Between-group comparison EG: participants were divided into two subgroups based on the severity of their motor impairment: 1. SG1: (P1–10) mild-to-moderate motor impairment. FM scores between 63 and 50. 2. SG2: (P11–20) a moderate (gross and some fine movement) to severe (gross motor function only) motor impairment. FM scores between 46 and 5	the arm subsection of the FM CSI	• SG1: practice resulted in an increase in trunk recruitment (either anterior displacement or rotation), which occurred in a situation where such recruitment was not required for the task. • Without particular attention to compensatory strategies, movement repetition training results in an increase in compensatory trunk use in those patients who tended to use more trunk displacement before training. • Motor function may be improved by repeated practice even in chronic stroke during a single session of intensive practice, but that therapy aimed at functional arm recovery should consist of a larger number of movement sessions for motor learning to occur. • Task-oriented training improves movement outcome and performance in patients with mild-to-moderate hemiparesis (no need for knowledge of performance), while motor performance (i.e. joint motion) might have to be explicitly addressed (i.e.

						knowledge of performance provided) for patients with more severe impairments.
(Hingtgen, McGuire, Wang, & Harris, 2006)	8	51.37±14.8 years	subjects had experienced a stroke and were scheduled to receive BOTOXs (Botulinum Toxin Type A)	Figure 2 subjects seated in a chair at a therapy table, and verbally instructed to place their hand against their sternum. Next, the patients were instructed to reach as far as they can at their own pace to the target directly in front of them. After reaching the target, the subjects end the reaching cycle with their hand against their sternum.	kinematic variables of movement time, range of motion, peak angular velocity, and percentage of reach where peak velocity occurs	• An UE kinematic model for motion analysis is proposed • The current model provides calculations of the joint angular velocity profile of reaching cycles. • The static and dynamic evaluation tests confirm the system's accuracy and precision in describing 3D upper extremity motion. • The current model was useful in detecting significant differences between affected and unaffected metrics (range of motion, peak angular velocity)
(Kamper, McKenna-Cole, Kahn, & Reinkensmeyer, 2002)	20	EG: 16 age from 30 to 85 years CG: 4	Chronic stroke patients from 9 months to 6 years and in arm impairment level from severe to mild.	Figure 3 Participants reached toward a screen of 75 targets spanning an approximate range from ± 90° side to side and from waist to head.	Chedoke-McMaster Stroke Arm Assessment, distance, velocity, smoothness, straightness, and direction of	• Reaches performed with the impaired arms showed significant degradation in all performance measures. Although only modestly dependent on the target location, these features correlated strongly with impairment level, as well as with each other. Reaching distance showed the strongest correlations with the other parameters.

					the hand path during each reach	• Stroke alters a broad array of features of reaching, yet largely the same degree of movement control is preserved across a range of target locations. The only consistently problematic task is to reach far out from the torso, independent of the movement direction.
(Leonard, Gardipee, Koontz, Anderson, & Wilkins, 2006)	13	mean age of 62.8 (SD 9.5) years	history of stroke with a diagnosis of spastic-type hemiparesis involving the upper extremity of at least 10 months' duration	Figure 4 Prospective, cross-sectional, correlation matrix using sample of convenience. subjects were positioned in an upper extremity armature for muscle stiffness, strength and co-contraction data collection during biceps and triceps brachii MVC trials, voluntary reaching to a target and during passive movements that mimicked the speed and trajectory of the subjects' voluntary movements.	FM-UE Motor, MAS, deep tendon reflexes, muscle stiffness, paresis and co-contraction during a voluntary reaching task and during passive movements.	• Paresis of the biceps and triceps brachii and co-contraction of the biceps brachii during voluntary reaching were the impairments most significantly correlated to motor performance. • It would appear that although increased passive muscle stiffness and decreased reflex thresholds are indeed present in individuals with chronic hemiparesis post stroke, these impairments do not appear to be the primary limitations during voluntary, unperturbed movement to a predicted target.

(Levin, 1996)	16	EG: 10 hemiparetic mean age was 48.5±9.3 years CG=6 age/sex matched	had sustained a single CVA leading to upper limb paresis	Figure 5 subjects were seated in front of a height-adjustable table. Movements started from the midline of the body at a distance of -15 cm from the chest. In the initial position, the shoulder was abducted 45°, the elbow was flexed 45° and the forearm was pronated so that the hand rested on the table. The near and far targets were placed in a sagittal direction 200 and 400 mm, respectively, away from the initial position. The ipsilateral and contralateral targets were placed 200 mm lateral to the near target in the ipsilateral and contralateral workspace, respectively	MAS FM	• for stroke patients having no perceptuomotor problems (apraxia, leftsided neglect), movement disruption occurs at the level of interjoint coordination and is not linked to pathological movement synergies. • treatment aimed at improving arm function should be oriented at restoring the normal sensorimotor relationships between the joints. • Once tone has been decreased, patients should practice coordinated movements with increasing difficulty and speed. • contrary to the traditional belief that muscle strengthening would only serve to augment spasticity and abnormal postural relationships, if administered at the appropriate time, specific strengthening of agonist muscles may be of benefit to the re-education of movement
(Sainburg & Kalakanis,	6	24–36 yr of age.	neurologically intact, right-	Figure 6	Beckman Instruments were used to	• After task adaptation, final position accuracy was similar for both hands; however, the hand trajectories and

2000)			handed adults	subjects sat facing a computer screen with each arm supported, over a horizontal table top at shoulder height, by a frictionless air-jet system. All joints distal to the elbow were immobilized using an air splint. The scapulae and trunk were immobilized using a custom-fit butterfly-shaped chest restraint.	monitor the elbow and shoulder joint angles.	joint coordination patterns during the movement were systematically different. The trajectories of both hands were not straight but exhibited oppositely directed curvatures. • Results show interlimb differences in the relative timing, magnitude, and direction of muscle torques at the shoulder and elbow that are more likely to result from differences in neural activation.

Abbreviations: CG - Control Group; CSI: the Composite Spasticity Index; EG - Experimental Group; FM: Fugl-Meyer; MVC: Maximal Voluntary Contraction; MAS: modified Ashworth scale; UL - Upper limb, UE - Upper extremity

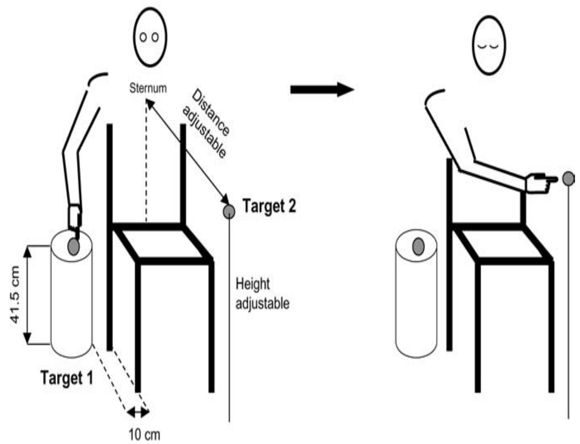

Figure 1

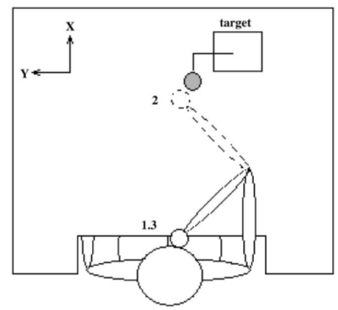

Figure 2

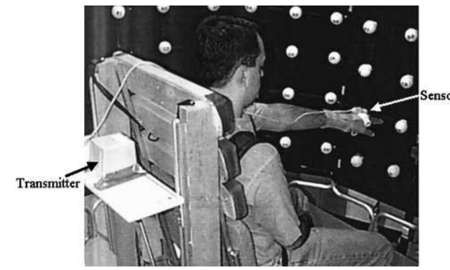

Figure 3

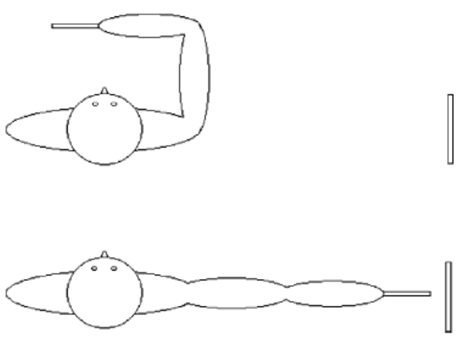

Figure 4

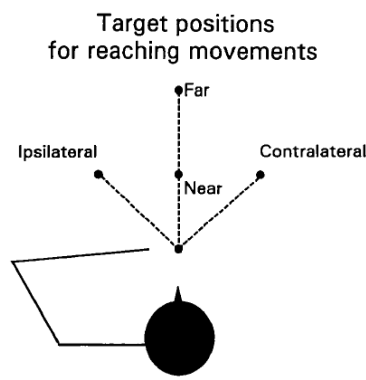

Figure 5

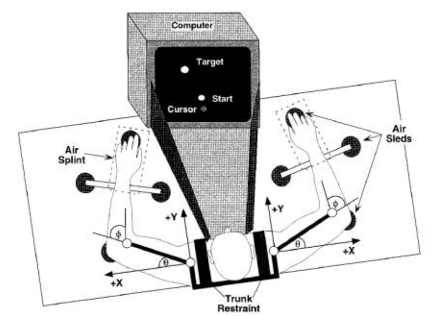

Figure 6

Appendix B: Text Descriptions

Figure 1.

Brief Description: The Armeo®Spring study setup

Summary Description: The study setup is illustrated with the Armeo®Spring device facing a computer to provide the testing software and a subject wearing the device.

Detailed Description: The study setup includes three main components. First, the Armeo®Spring device which is a gravity-supporting exoskeleton apparatus that contains no robotic actuators. It is the commercialized product of Therapy Wilmington Robotic Exoskeleton (T-WREX) (Housman, Scott, & Reinkensmeyer, 2009) which has been re-designed by Hocoma, Inc. with user-friendly software and hardware interface to be used in the routine clinical settings. The main structure of the device consists of an arm exoskeleton with integrated springs providing a 5 degree-of-freedom movement at the shoulder, elbow, and wrist levels. It embraces the whole arm, from shoulder to hand, and counterbalances the weight of the patient's arm providing a sense of arm flotation at all positions in the available workspace. The second component is a computer facing the Armeo®Spring device with its display being set at the level of the subject's eyes to provide the testing software for the study. The third component is the subject who is wearing the Armeo®Spring device while seated on a chair and facing the display of the computer.

Figure 2.

Brief Description: Armeo®Spring weight support system.

Summary Description: The Armeo®Spring device contains two weight support systems at the upper arm level and the forearm level.

Detailed Description: The main structure of the Armeo®Spring device consists of an arm exoskeleton with integrated springs providing a 5 degree-of-freedom movement at the shoulder, elbow, and wrist levels. It embraces the whole arm, from shoulder to hand, and counterbalances the weight of the patient's arm providing a sense of arm flotation at all positions in the available workspace. The upper arm support provided by an integrated spring contains multiple level of support. These levels are displayed on the device as a scale from A to K, with A is the minimum level of support and K is the maximum. The forearm support contains a scale from 1 to 5 displayed on the device with 1 is the minimum level of support and 5 is the maximum.

Figure 3.

Brief Description: The print screen of the fruit shopping game.

Summary Description: The fruit shopping game is the software that was used for testing subjects while using the Armeo®Spring device.

Detailed Description: The fruit shopping game is about picking apples and placing them in a shopping cart. The apples are green in color and will show up one at a time across a computer screen while the shopping cart is placed at the lower left corner of the screen. To complete the game, the user should move a hand-like pointer using the Armeo®Spring from the initial *start* position to *reach* an apple that turns from green to red in color. When the pointer is over the red apple, the user should *squeeze/grasp* the pressure sensitive handgrip of the Armeo®Spring device to hold the apple and *transport* the apple to the shopping cart. When the color of the cart changes the user should take the pressure off the device handgrip to *release* the apple. This process is illustrated in five phases shown in the figure; the initiation, reaching, grasping, transporting and releasing phase.

Figure 4.

Brief Description: The mean completion time between the two gravity-support levels.

Summary Description: The mean time needed to complete each phase of the reaching cycle and the total mean duration needed to complete the reaching cycle for a healthy subject and a stroke subject under the mild and moderate level of support provided by the Armeo®Spring device is displayed in column graph.

Detailed Description: The mean time needed to complete each phase of the reaching cycle and the total mean duration needed to complete the reaching cycle for a healthy subject and a stroke subject under the mild and moderate level of support provided by the Armeo®Spring device is displayed in column graph. The x-axis represents the four phases of the reaching cycle (Initiation, Reaching, Grasping, and Transporting) and the total duration. In each phase and the total duration, four columns are displayed side by side. The first column is blue in color and represents the healthy subject while using the mild weight-support. The second column is red in color and represents the healthy subject while using the moderate level of support. The third one is green in color and represents the stroke subject while using the mild weight-support and the last column is purple in color and represents the stroke subject while using the moderate level of weight-support. The y-axis represents the time in seconds.

Figure 5.

Brief Description: Joint angle changes during the reaching cycle for the healthy subject (upper panel) and the stroke subject (lower panel).

Summary Description: The joint angle changes during the reaching cycle are displayed in a graph. The upper panel represents the changes in the joint angles for the healthy subject and the lower panel represents the changes in joint angles for the stroke subject.

Detailed Description: The joint angle changes during the reaching cycle are displayed in a graph. The graph is divided to two panels, the upper panel represents the changes in the joint angles for the healthy subject and the lower panel represents the changes in joint angles for the stroke subject. Each panel displays three line charts sorted vertically. The top chart represents the changes in abduction/adduction angles of the shoulder joint. The middle chart represents the changes in flexion angles of the shoulder joint and the lower chart represents the changes in flexion angles of the elbow joint. In each chart, two lines are displayed; a blue line which represents the joint angles under the mild weight-support and a red line which represents the joint angles under the moderate weight-support. The x-axis in each chart represents the changes in joint angles as a percentage of the reaching cycle. The y-axis represents the level of change in joint angles in degrees.