Biomedical Engineering: Applications, Basis and Communications, Vol. 23, No. 6 (2011) 457–466
DOI: 10.1142/S1016237211002876



# GRASP COORDINATION IN VIRTUAL ENVIRONMENTS FOR ROBOT-AIDED UPPER EXTREMITY REHABILITATION

Janez Podobnik*, Domen Novak and Marko Munih
*Laboratory of Robotics, Faculty of Electrical Engineering*
*University of Ljubljana, Tržaška c. 25, Ljubljana, Slovenia*

Accepted 22 September 2011

## ABSTRACT

This paper explores grasping in robot-aided upper extremity rehabilitation, with a special focus on reaching and grasping exercises and the coordination between load force and grasp force. Six healthy subjects and two hemiparetic subjects performed "pick and place" movements with a haptic robot and virtual environment. These movements were segmented into three phases: grasping, transport and release phase, and the correlation between grasp and load force was calculated over the entire movement and within each phase separately. Results show that the subjects employ same basic mechanism of grasp and load force coordination during a virtual task as in real situations. However, the grasp and load force are partially decoupled due to the nature of the grasping device and the complexity of the task. Furthermore, the coordination is different in different phases and also depends on the level of impairment as well as the level of active support by the rehabilitation robot. The first hemiparetic subject, who can perform reaching movements but cannot open the hand, thus has a lower correlation between grasp force and load force than healthy subjects only in the release phase while the second hemiparetic subject, who has little arm mobility, has a lower correlation in all three phases. Thus, the current work provides basic empirical knowledge that can serve as a basis for future research and for the design of robot-aided reaching and grasping tasks.

*Keywords*: Haptic interfaces; Rehabilitation robotics; Upper extremities; Grasping.

## INTRODUCTION

Rehabilitation robotics has become widely recognized as a novel and promising motor rehabilitation approach.[1–3] Its aim is to improve the patient's motor performance, shorten rehabilitation time, and provide objective parameters for patient evaluation.[4–6] As early as 2003, the Gentle/S project showed that subjects are motivated to exercise for longer periods of time when using a rehabilitation robot. However, no grasp training was included in the Gentle/S prototype, and this was identified as one of the major shortcomings of the project.[7] Today, there is an ever increasing number of arm movement or grasp training devices. However, only a limited number of devices allow simultaneous rehabilitation of both reaching and grasping motions.

One well-known combined reaching and grasping device is the Gentle/G system,[8] which combines the Gentle/S system with a dedicated grasping assistance unit, the Grasp Robot Exoskeleton. This exoskeleton has three passive and three active degrees of freedom (DOF). The hand and forearm are placed on a padded wrist splint while the fingers are placed onto supports which incorporate force sensors. The index, middle, ring and small finger are then actuated simultaneously in 2

*Corresponding author: Janez Podobnik, Laboratory of Robotics, Faculty of Electrical Engineering, University of Ljubljana, Tržaška c. 25, Ljubljana, Slovenia. E-mail: janezp@robo.fe.uni-lj.si

DOF while the thumb is actuated separately in 1 DOF. Another well-known reaching and grasping device is a hand module for the MIT-MANUS arm rehabilitation device.[9] Dubbed alpha-prototype I, the module was designed with eight active DOF but was found too cumbersome for clinical use. A new simplified alpha-prototype II was thus designed with one active DOF, limiting it to grasp and release. Other examples of reaching and grasping devices include the ARMEO robot, which uses a passive pressure-sensitive handgrip for measuring the grasp force applied with the hand,[10] the L-EXOS exoskeleton, which uses an active hand-exoskeleton that can apply forces on two fingertips (thumb and index finger),[11] and the IntelliArm whole-arm exoskeleton, which uses a 2 DOF active mechanism that allows hand opening and closing motions.[12]

Though some of these grasping devices are mechanically quite complex, they are used only as on-off devices that indicate the grasp or release of objects in virtual environments. The object is grasped when the applied grasp force is larger than a predefined grasp threshold and released when the grasp force is lower than a release threshold. No effort has been made to extract additional information from the grasp force, and no effort has been made to examine any connections between the grasp force and other forces exerted by the user (particularly the load force). However, this information could be useful during rehabilitation and has been extensively studied in real-world grasping tasks performed by healthy subjects.

Forssberg *et al.*[13] described basic mechanisms of coordination between grasp force (the force exerted by the human in the normal direction with regard to the surface of the object) and load force (the force exerted by the human in the tangential direction opposite of gravitation with regard to the surface of the object) for children and adult subjects in the grasping phase of a pick-and-place movement. The same study showed that, in the grasping phase, healthy adult subjects employ parallel coordination of the grasp and load force in a nearly linear relationship. Furthermore, when transporting objects, the grasp force increases in parallel with the load force.[14,15] However, Rost *et al.*[16] showed that the relationship between grasp and load force is weaker in subjects with impaired arm function — precisely the same type of subjects that would use a rehabilitation device. Thus, the goal of this paper is to determine how the findings of Forssberg *et al.*[13] and Rost *et al.*[16] regarding grasp and load force extend to an actual rehabilitation task performed in a virtual environment by both healthy subjects and stroke victims.

## MATERIALS AND METHODS

### Subjects

Two hemiparetic post-stroke subjects with chronic upper extremity impairments were recruited: a 40-year-old woman (subject A) and a 45-year-old man (subject B), 5 and 7 years after stroke. On the upper limb motor performance section of the Fugl-Meyer assessment scale.[17] Subject A scored 48 out of 66 while subject B scored 19 out of 66. For both subjects, the right arm was impaired and had been the dominant arm before the stroke.

Six healthy subjects (all male, age 26−29 years) with no known neuromuscular disorders also participated in the experiments. All had normal or corrected-to-normal vision and were right-handed.

### Hardware

The system consists of the following components:

- The HapticMaster haptic interface developed by MOOG FCS. The HapticMaster is a commercially available haptic robot with three active DOF. A 3-axis force sensor with measuring range of 100 N, which is originally built into HapticMaster at the end-effector, was used to measure the interaction force applied by the user.
- The grasping device (mounted on the force sensor at the end-point of the haptic interface) measures the grasp force applied by the user.
- The arm weight compensation system. This system was designed and built at the Laboratory of Robotics and is an active system equipped with two rotary motors (one for the lower and one for the upper arm). Each motor is equipped with a winch and an encoder with a resolution of 512 counts per revolution. Encoder outputs are used within the controller to implement the arm gravity compensation. A wire is attached with one end to the winch and the other end to the cuff, thus supporting the lower or upper arm.
- A 3D projection system for visualization of graphical virtual environments. This system consists of two InFocus projectors, a back projection screen and a multimedia computer. The system enables generation of visual 3D virtual environments. The backprojection screen is 2 meters high and 1.5 meters wide and is positioned 1.7 meters from the user. Circular polarizing filters are placed in front of the projectors and the user wears glasses with circular polarizing filters.

The grasping device is a passive mechanism mounted on the force sensor at the end-point of the haptic interface.

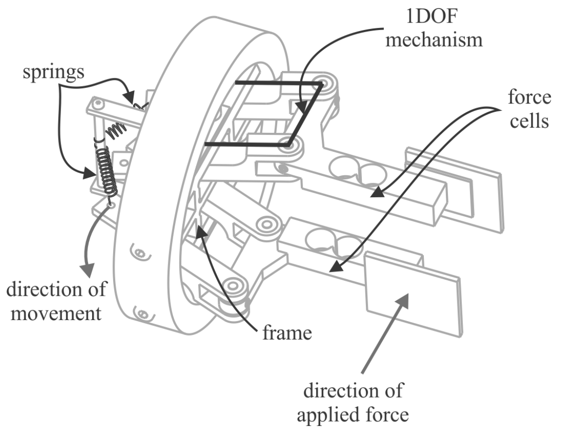


**Fig. 1** The basic mechanism of the grasp device. The grasping device consists of a two-degrees of freedom mechanism for measuring the grasp force. Springs attached to the mechanism on the back of the grasping device are used for a passive haptic rendering.

It enables grasping of virtual objects in virtual environments. Figure 1 shows the passive mechanism of the device, consisting of two one-degree-of-freedom parallelogram mechanisms mounted on the frame of the grasping device (Fig. 1, one of the mechanisms is indicated with a bold line). Each of the two mechanisms is equipped with a force cell, which are commonly used in devices for measuring the grasp force.[18] Each force cell measures the force applied to the pads. The mechanisms allow the finger pads to remain in parallel regardless of the distance between them. The user applies force to the first cell with the thumb and to the second cell with the other four fingers. A cylindrical cuff holds the thumb while a plate cuff holds the other four fingers. The entire mechanism can be used for either the left or right hand. Though different finger cuffs have to be used for each hand, the process of replacing the cuffs requires only a few minutes.

Each of the parallelogram mechanisms is connected to the back of the frame via springs as shown in Fig. 1. Therefore, the device can be described as a passive elastic haptic device. Lindeman *et al.*[19] described a passive haptic device as a physical object that provides haptic feedback to the user through its forms, surface texture and other properties. Haptic feedback conveyed by the device is not rendered by a controller but is instead determined by the inherent properties of the device. The device therefore allows indirect interaction with simulated objects and the execution of grasping movements. Eng *et al.*[20] have shown that a noticeable connection between generated motor action and observed effects in virtual reality leads to better performance improves the usability of the device and leads to a higher engagement of motor neurons.

The coefficients of the springs were 4.5 N/cm. Maximal distance between finger cuffs was adjustable and was adjusted for each individual subject. The typical maximal distance between the pads was 10 cm. Minimal distance between cuffs was limited to 3.4 cm with a pin. The pin was positioned in the frame of the parallelogram mechanism so that the force cell continued to measure grasp force applied by the user, even though the movement of the parallelogram mechanism was limited.

The grasping device's frame is mounted on the wrist support mechanism as shown in Fig. 2. The user places the wrist in a splint that limits wrist movement but does not affect finger mobility. The wrist support mechanism has two passive DOF and allows free mobility in the elbow and shoulder.

## Pick-and-Place Task

The pick-and-place task (Fig. 3) requires the subject to perform "reach-and-grasp" movements. It incorporates arm movement without grasp force (movement to the virtual object), grasping the virtual object, arm movement with applied grasp force (transporting the grasped object to a new location), and releasing the virtual object. The subject must first move the robot with the arm to the virtual object (an apple which has fallen from a tree). When he or she comes into contact with the apple, he or she must grasp it. When a sufficient grasp force is applied, the virtual fingers become blue, signaling to the subject that he or she can proceed. Then, the subject must transport the apple to a designated location (a fruit stand) and release it there. If the subject does not apply a sufficiently large grasp force during transport, the apple falls down and has to be picked up

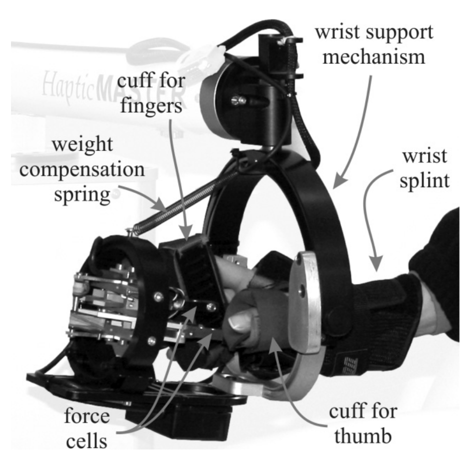


**Fig. 2** The grasping device and wrist support mechanism mounted on the end-point of the HapticMaster robot.

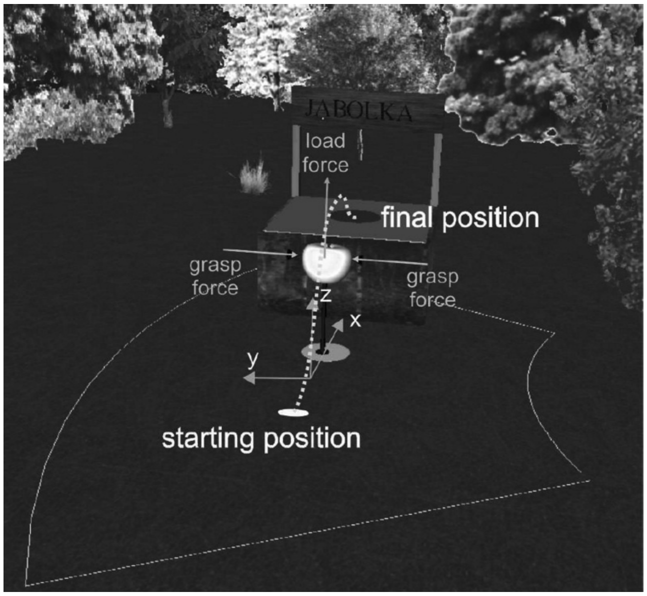


**Fig. 3** The pick-and-place task. The subject has to pick apples which fall from a tree and place them on the platter atop the fruit stand. A reference coordinate system is shown on the figure and the forces applied on the virtual object.

again. When the apple is placed on the designated place (a platter), it can be released. Once the apple is released, a new apple appears in a random position. The subject must again reach for and transport it to the designated location.

## Robotic Assistance

Not all physically impaired subjects can be expected to successfully perform a pick-and-place movement. Thus, the pick-and-place task includes a robotic assistance system that helps the subject move his or her arm when needed. Specifically, the assistance helps the subject move the apple from the ground to the platter. As this is a vertical movement, it is more difficult than simply reaching the apple (which is a movement in the horizontal plane). The assistance consists of two components:

- A constrained haptic path which prevents the subject from deviating strongly from an 'ideal' trajectory between the ground and the platter. Movement along the haptic path is unconstrained while every deviation from the path is constrained with a force proportional to the deviation from the path. The 'ideal' trajectories were generated from unconstrained, natural human arm movement paths of healthy subjects using B-spline approximation. These movements were the same pick-and-place movements in the same task, but performed with the HapticMaster's virtual impendence set to the lowest possible value that still ensures stable haptic interaction. Thus, the subjects could move freely in the workspace of the robot. They were instructed to move the arm as naturally as possible. A total of 100 pick-and-place trajectories were recorded, and the average trajectory was extracted by averaging all 100. B-spline approximation was then used to parametrically define the measured unconstrained human arm movement trajectory. This haptic path is further described in Ziherl *et al.*[21] and can be considered as a way to increase the efficiency of the subjects' movements. Lang *et al.*[22] defined an efficient movement as one that moves directly toward the target without extraneous or abnormally circuitous movements. By preventing the subject from deviating too much from a normal, healthy trajectory, the haptic path ensures efficient movement.
- A force field that actively moves the subject's arm along the haptic path. Since the haptic path only constrains movement and does not encourage it, this force field is required for subjects who are unable to move the arm by themselves or can only move the arm part of the way to the platter. The force field is based on the minimum jerk index, which ensures smooth movements, and is described further in Mihelj *et al.*[23]

During the first, introductory session, both subjects A and B initially performed several motions without the minimum jerk force field. In these initial trials, subject A successfully grasped all of the apples and placed them on the stand. Thus, the minimum jerk force field was not applied for this subject in subsequent sessions. However, subject B was unable to complete a single initial trial without the minimum jerk force field due to the severity of impairment. Thus, the minimum jerk force field was applied for this subject in all subsequent sessions.

## Procedures

Figure 4 shows the training setup with a hemiparetic subject. The task with all required steps was first explained to the subject. Then, he/she was seated in a chair in front of the haptic interface. The arm weight compensation cuffs were attached. The wrist was placed in a splint and securely fixed to the wrist support mechanism. The fingers were positioned in the finger cuffs of the grasping device. Each healthy subject participated in one training session while subject A

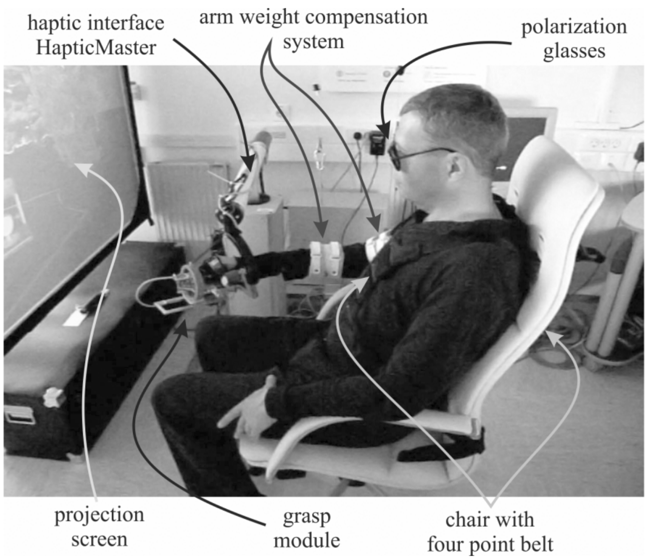


**Fig. 4** The training setup with a hemiparetic subject.

participated in 9 training sessions and subject B participated in 10 training sessions. Sessions were performed twice a week (Monday and Thursday). Each session consisted of 80 pick-and-place movements, with a 2.5 min pause after each 20 movements.

For healthy subjects, the grasp threshold was always set to 10 N while the release threshold was always set to 6 N. In experiments performed by subjects A and B, the grasp and release thresholds were set based on self-evaluation. In the first session, both the grasp and release thresholds were set to 6 N for both subjects. Based on the subjects' self-evaluation, the grasp force was increased and the release force decreased if the subject was confident that the thresholds were set too high (release threshold) or too low (grasp threshold). The amount by which the threshold was increased or decreased was determined based on the performance of the subject in the previous session (observed maximal grasp force after the grasp of virtual object and observed minimal grasp force after the release of the virtual object). This was done independently for subjects A and B.

## Data Analysis

The robot end-point position, the interaction force and the grasp force applied by the user were sampled with a frequency of 250 Hz and filtered in Matlab with a cutoff frequency of 40 Hz. The load force is the z-component of the interaction force applied by the user. For the two stroke subjects, data from the first, introductory session were not recorded. For subject A, $8 \times \text{session} \times 4\,\text{task} \times 20\,\text{apples} = 640$ pick-and-place movements were recorded. For subject B, $9 \times \text{session} \times 4\,\text{task} \times 20\,\text{apples} = 720$ pick-and-place movements were recorded.

Each pick-and-place movement was segmented into three phases.

- Grasping phase. First, the subject must come into contact with the virtual object. Then, the grasping phase begins when the subject starts to increase the grasp force. To grasp the object, the grasp force must exceed the grasp threshold. The load force remains at a baseline of around 0 N until the object is grasped, then starts to increase, but does not yet reach its maximum value. The grasp force, on the other hand, reaches its maximum value in this phase.
- Transport phase. This phase begins when the subject lifts the virtual object from the ground. The load force becomes large enough to oppose the virtual gravity, which acts on the object in the opposite direction of the load force. The load force reaches its maximum value early in the phase. When the object is moved, inertial loads arise and result in variations of the load force. The grasp force slowly decreases, but does not fall below the release threshold, which is the minimal force needed to hold the object. All arm movement is performed in this phase. The phase ends when the object reaches the designated final position.
- Release phase is the last phase, in which the subject releases the virtual object. The grasp force decreases faster than during the transport phase. The object is released when the grasp force drops below the grasp force release threshold. The position is held constant while the load force drops to 0 N once the object is placed on the ground.

Segmentation was performed as follows: 60 random pick-and-place movements from healthy subjects as well as 20 movements from each of the two stroke subjects were segmented manually by an expert. These were then used as a training data set for a simple algorithm based on linear discriminant analysis which then automatically segmented all remaining signals. The results of the algorithm were checked, and any visible errors in segmentation were corrected manually.

The mean and standard deviation of the correlation coefficients between load force and grasp force were calculated during the three phases for all subjects. Correlation is a sensitive parameter for precision of the coupling between the grasp and load force.[24] Furthermore, regression analysis of grasp force and load force was performed, and the $R^2$ coefficient of determination was calculated in the same way as done by Forssberg *et al.*[13] Student's T-test was used to assess differences between subjects or different phases.

## RESULTS

### Phases of the Pick-and-Place Task

Figure 5 shows the grasp force, wrist position and load force for 20 consecutive pick-and-place movements for subject B, subject A and healthy subject. X-axes of Fig. 5 are shown in normalized time.

For the first session of subject A, the grasp threshold was set to 6 N while the average maximal force after the grasp of the virtual object was 13.5 N. For the last session of subject A, the grasp threshold was set to 16 N while the average maximal force after the grasp of the virtual object was 17.5 N. For the first session of subject B, the grasp threshold in the first session was set to 6 N while the average maximal force after the grasp of the virtual object was 7.9 N. For the last session of subject B, the grasp threshold was set to 16 N while the average maximal force after the grasp of the virtual object was 21.4 N. The change in the observed maximal force from the first to the last session was statistically significant for both subjects ($p < 0.01$).

For the first session of subject A, the release threshold was set to 6 N while the average minimal force after the release of the virtual object was 5.7 N. For the last session of subject A, the release threshold was set to 3.4 N while the average minimal force after the release of the virtual object was 2.7 N. For the first session of subject B, the release threshold was set to 6 N while the average minimal force after the release of the virtual object was 4.9 N. For the last session of subject B, the release threshold was set to 3.8 N while the average maximal force after the grasp of the virtual object was 3.65 N. The change in observed minimal force from the first to the last session was statistically significant for both subjects ($p < 0.01$).

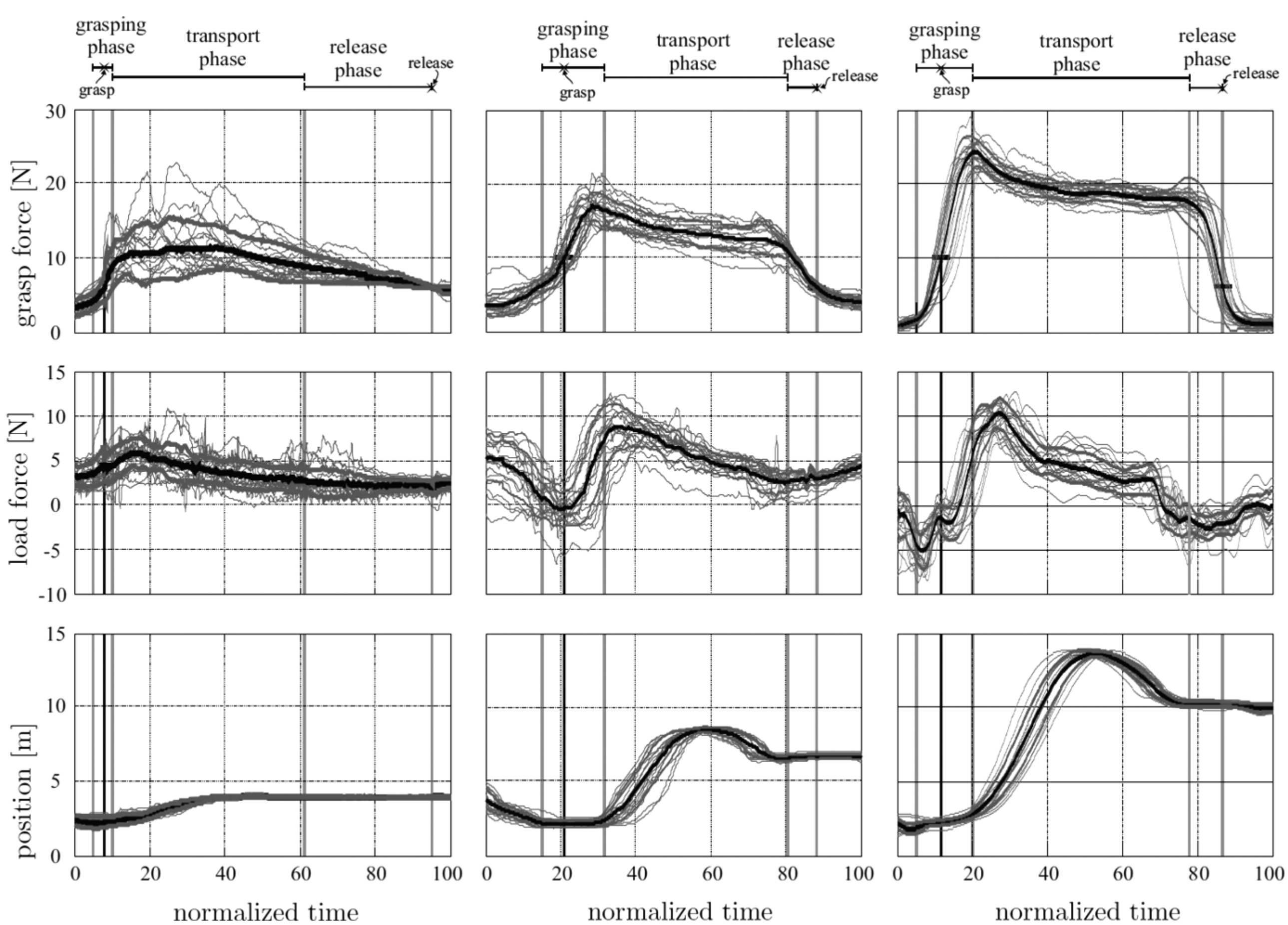


**Fig. 5** The grasp force, the position of the end-point of the HapticMaster and the load force applied by the subjects are shown on the figure. First column shows results of subject B, second column of subject A and third column shows results of healthy subject. Signals are presented in normalized time from 0% to 100% of the pick and place movement.

**Table 1. Correlation Coefficients and $R^2$ Coefficients Between Grasp and Load Forces During the Different Phases and During the Full Pick-and-Place Movement.**

| Subjects | Phase | Correlation Coefficients for a Given Phase | $R^2$ for a Given Phase | Correlation Coefficients Full Movement | $R^2$ for a Full Movement |
|---|---|---|---|---|---|
| Controls | Grasping phase | 0.69 (0.24) | 0.67 (0.26) | 0.75 (0.17) | 0.50 (0.21) |
| | Transport phase | 0.62 (0.24) | 0.58 (0.30) | | |
| | Release phase | 0.56 (0.41) | 0.16 (0.28) | | |
| Controls (with haptic path) | Grasping phase | 0.66 (0.43) | 0.62 (0.28) | 0.71 (0.28) | 0.48 (0.25) |
| | Transport phase | 0.66 (0.35) | 0.57 (0.25) | | |
| | Release phase | 0.32 (0.47) | 0.08 (0.34) | | |
| Subject A | Grasping phase | 0.65 (0.32) | 0.39 (0.25) | 0.56 (0.29) | 0.32 (0.23) |
| | Transport phase | 0.76 (0.33) | 0.66 (0.28) | | |
| | Release phase | 0.11 (0.63) | 0.21 (0.25) | | |
| Subject B | Grasping phase | 0.23 (0.62) | 0.30 (0.30) | 0.25 (0.61) | 0.36 (0.29) |
| | Transport phase | 0.17 (0.65) | 0.18 (0.27) | | |
| | Release phase | 0.10 (0.77) | 0.17 (0.26) | | |

## Coordination between Grasp and Load Force

Table 1 shows correlation and regression coefficients between grasp and load force for healthy subjects and for subjects A and B. The third column gives correlation coefficients for individual phases, the fourth column gives the $R^2$ coefficient of determination for individual phases, the fifth column gives correlation coefficients for the entire pick-and-place movement, and the sixth column gives the $R^2$ coefficient for the entire pick-and-place movement. Results for healthy subjects are given for the pick-and-place task without and with the haptic path. Correlation and regression coefficients for the entire pick-and-place movement with haptic path and without haptic path do not differ significantly ($p = 0.09$). In the individual phases, correlation and regression coefficients with haptic path and without haptic path do not differ significantly in the grasping and transport phases. Correlation and regression coefficients with haptic path and without haptic path do however differ significantly in the release phase ($p < 0.01$ for both coefficients).

# DISCUSSION

## Interpretation of Results

Forssberg *et al.*[13] showed that healthy adult subjects exhibit a nearly linear relationship between grasp and load force in the grasping phase. In our experiments, we can observe similar relationships between grasp and load forces, showing that subjects lifting an object in a virtual task also employ anticipatory control of the force output during the grasping phase. The grasp and load forces in hemiparetic subjects rise in parallel, showing that lift synergies are employed, although correlation and regression coefficients between grasp and load force for subject B are low with a large standard deviation (see Table 1) due to large variations of load and grasp forces. Comparison of the correlation and regression coefficients with and without the haptic path shows that the coordination between grasp and load forces is not significantly affected by the haptic path over the entire pick-and-place movement. Closer inspection reveals that coordination is not affected by the haptic path in the grasping and transport phases, but is affected by the haptic path in the release phase. In the release phase, load force is small since the virtual object rests on the ground. Variations in load force are therefore relatively larger than in the other two phases where load force is larger. These variations affect the correlation between grasp and load forces in the release phase. In control subjects, this phase is short (9−12% of the full movement) and does not affect the correlation or regression coefficient for the whole movement. However, this phase is longer in hemiparetic subjects with an impaired ability to release the object. Thus, it is crucial to divide the full movement into phases so that coordination between grasp and load forces can be properly examined. In subject A, the correlation and regression coefficients for the whole movement are significantly lower than in control subjects, indicating that coordination is impaired. However, a deeper look shows that these coefficients are similar in both healthy subjects and subject A during the grasping and transport phases. The difference between healthy subjects and subject A occurs only in the release phase. This is not because of impaired coordination, but because of an impaired ability to open the hand. As a result of this impairment, the release phase is prolonged and the correlation and regression coefficients for the whole movement decrease despite normal coordination in the other phases. For subject B, coordination between grasp and load forces is degraded in all phases of the movement. The subject was unable to lift the arm and required haptic assistance from the robot. Therefore, he was unable to fully control the load force, resulting in degraded coordination between grasp and load forces.

## Comparison with Previous Studies

The correlation and regression coefficients obtained in our study are markedly lower than in the work of Forssberg *et al.*,[13] who calculated $R^2$ values of over 0.95. Furthermore, they are lower than those in our own previous work (Podobnik *et al.*[24]), where correlation coefficients of upto 0.99 were obtained using the same calculation method. In the present study, correlation coefficients of 0.75 and $R^2$ values of 0.5 are obtained for full movements of healthy subjects. However, this is not as surprising as it may first appear.

The quality of the relationship between grasp and load force appears to depend on the complexity of the action performed. Forssberg *et al.*[13] required the subjects to only lift the object vertically. In our previous work (Podobnik *et al.*[24]), we also performed simple trials where the subject had to linearly increase the grasp force and obtained correlation coefficients of up to 0.99 (though $R^2$ values were not calculated). However, in more complex trials where the grasp force changed dynamically, correlation coefficients decreased to as low as 0.65 for some healthy subjects. Thus, in our reaching and grasping movements, which are also complex, a correlation coefficient of 0.75 and a relatively low $R^2$ value compared to Forssberg *et al.*[13] is not unrealistic. However, it does raise the issue of how useful observing the relationship between grasp force and load force would be in rehabilitation robotics, as it appears overall weaker than in real-world tasks.

In addition to the complexity of the task, we must also point out another factor that likely affected correlation and regression coefficients: unlike in real-world tasks, the grasp and load forces were partially decoupled in our virtual task. When transporting actual objects held with the fingers, the grasp force increases in parallel with the load force.[14,15] In experiments performed by Flanagan *et al.*[14] and Nowak *et al.*,[15] both grasp and load forces are applied by the fingers. In our experiments, the grasp force is also applied by the fingers. However, the load force is the force between the wrist and the end-point of the haptic interface. Thus, subjects do not feel the changes in the load force with the fingers, but with the wrist. Therefore, the grasp force and the load force are decoupled since they are felt by different parts of the body. However, this arrangement was necessary for successful use of the device for upper extremity rehabilitation where wrist support is required.

The results for the two stroke subjects show even worse correlation and regression coefficients than for healthy subjects. However, segmentation of the movements into different phases shows that these coefficients are lower in phases where the subject's ability is impaired (the release phase for subject A, all phases in subject B). Notably, subject A exhibits similar correlation and regression coefficients as healthy subjects in the grasping and transport phases. Furthermore, Fig. 5 shows similar dynamic behavior in grasp and load forces for healthy subjects and subject A. As Rost *et al.*[16] showed, the relationship between grasp and load forces is weaker in subjects with impaired arm function, and it makes sense that this decrease is most prominent in phases where the impairment most strongly affects the movement. Thus, it would appear that the correlation and regression coefficients can be used to identify the phases of the movement in which arm coordination is impaired.

Finally, a note on the dynamics of grasp and load forces. During normally developed grip-lift synergy, grasp and load forces are initiated simultaneously. This is followed by a smooth and parallel increase in both the grasp and load force employing anticipatory control of the neuro-muscular system of the upper extremity. In contrast, abnormally developed or impaired coordination is characterized by a sequential order of grasp and load force increase is observed.[25] The peak of the grasp force is more prominent in healthy subjects and subject A and is about 25% higher than the baseline grasp force during the transport phase. In subject B, a number of peaks are present in the grasp force and can occur in either the grasp phase or transport phase. The averaged profile (see first column of Fig. 5) shows that, once the peak of grasp force has been reached in the grasp phase, the grasp force remains constant during the transport phase.

## Study Limitations

Some of the limitations of our study should be highlighted. First of all, the group of healthy subjects is relatively homogenous and younger than the two stroke subjects. If grasp force coordination changes with age, such young subjects might not be appropriate. However, previous studies have shown that the majority of grasp force changes occur after 60 years of age, though some are noticeable after 50 years of age. Mathiowetz *et al.*,[26] for instance, found no differences in grasp force strength between an age group of 25−29 years and an age group of 40−44 years. Many other studies also group subjects under 50 years of age together (e.g. Ref. 27). Cole *et al.*[28] concluded that the changes in grasp force after the age of 50 can be explained by the reduced skin hydration and the resultant decrease in friction between the fingers and object. Subjects compensate for this by increasing the grasp force. This should not be a factor in our study since the subject's hand is fixed to the robot in the wrist. Thus, we feel that there should be no age-related differences between the healthy and stroke subjects in our study, though we acknowledge that our results may not generalize to an even older (50+) subject group.

The second limitation is in the segmentation of movements into three discrete phases. Although the phases themselves have been established by Forssberg *et al.*,[13] who based their definitions on previous work in the field, there is no strict method or rule on how segmentation should be performed. We chose to perform a mixture of manual and automatic segmentation in order to make use of expert knowledge while avoiding the time-consuming task of manually segmenting over a thousand pick-and-place movements. However, with no standardized rule on movement segmentation, it is difficult to ensure that our findings from the different phases correspond perfectly to other studies that may perform the segmentation differently.

## CONCLUSIONS

This paper presents a study of pick-and-place movements in a virtual environment for upper extremity rehabilitation, with a focus on the coordination between grasp and load forces. In healthy subjects grasping real objects, these two forces have a nearly linear relationship. However, our results show that, due to the nature of the haptic interface for upper extremity rehabilitation (wrist support) and the complexity of the task, the relationship between grasp and load forces is weaker in robot-aided training. Nonetheless, the subjects do employ basic mechanisms of grasp and load force coordination. Furthermore, the pick-and-place movements can be segmented into three different phases with different patterns of grasp and load force coordination. These phases are effective in separating and quantifying differences among users with different levels of physical capability, and could provide means of identifying key areas for interface improvement and provide a theoretical basis for developing methods of haptic assistance.

## ACKNOWLEDGMENTS

The authors acknowledge the financial support from the Slovenian Research Agency (ARRS).

## REFERENCES

1. Riener R, Nef T, Colombo G, Robot-aided neurorehabilitation of the upper extremities, *Med Biol Eng Comput* **43**:2−10, 2005.
2. Krakauer JW, Motor learning: Its relevance to stroke recovery and neurorehabilitation, *Curr Opin Neurol* **19**:84−90, 2006.
3. Kwakkel G, Kollen BJ, Krebs HI, Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review, *Neurorehabil Neural Repair* **22**:111−121, 2008.
4. Harwin WS, Patton JL, Edgerton VR, Challenges and Opportunities for Robot-Mediated Neurorehabilitation, *Proceedings of the IEEE* **94**:1717−1726, 2006.
5. Kahn LE, Zygman ML, Rymer WZ, Reinkensmeyer DJ, Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: A randomized controlled pilot study, *J Neuroengineering Rehabil* **3**, 2006.
6. Hsieh MS, Chen CJ, Tsai MD, A hand rehabilitation computer system using commercial haptic device, *Biomed Eng-App Bas C* **19**:375−382, 2007.
7. Loureiro RCV, Upper Limb Mediated Stroke Therapy — GENTLE/s Approach, *Journal of Autonomous Robots* **15**:35−51, 2003.
8. Loureiro RCV, Lamperd B, Collin C, Harwin WS, Reach & Grasp Therapy: Effects of the Gentle/G System Assessing Sub-acute Stroke Whole-arm Rehabilitation, in *IEEE 11th International Conference on Rehabilitation Robotics*, Kyoto, Japan, pp. 755−760, 2009.
9. Masia L, Krebs HI, Cappa P, Hogan N, Whole-Arm Rehabilitation Following Stroke: Hand Module, in *IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, pp. 1085−1089, 2006.
10. Gijbels D, Lamers I, Kerkhofs L, Alders 1 G, Knippenberg E, Feys P, The Armeo Spring as training tool to improve upper limb functionality in multiple sclerosis: A pilot study, *J Neuroeng Rehabil* **8**, 2011.
11. Frisoli A, Rocchi F, Marcheschi S, Dettori A, Salsedo F, Bergamasco M, A new force-feedback arm exoskeleton for haptic interaction in virtual environments, in *Proceedings of WHC 2005, 1st Joint Conference on Haptics*, pp. 195−201, 2005.
12. Ren Z, Park HS, Zhang LQ, Developing a whole-arm exoskeleton robot with hand opening and closing mechanism for upper limb stroke rehabilitation, in *IEEE International Conference on Rehabilitation Robotics*, pp. 761−765, 2009.

13. Forssberg H, Eliasson AC, Kinoshita H, Johansson RS, Westling G, Development of human precision grip. I: Basic coordination of force, *Exp Brain Res* **85**:451−457, 1991.
14. Flanagan JR, Wing AM, Modulation of grip force with load force during point-to-point arm movements, *Exp Brain Res* **55**:131−143, 1993.
15. Nowak DA, Glasauer S, Hermsdorfer J, How predictive is grip force control in the complete absence of somatosensory feedback? *Brain* **127**:182−192, 2004.
16. Rost K, Nowak DA, Timmann D, Hermsdörfer J, Preserved and impaired aspects of predictive grip force control in cerebellar patients, *Clin Neurophysiol* **116**:1405−1414, 2005.
17. Fugl-Meyer AR, Jsk L, Leyman I, Olsson S, Steglind S, The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance, *Scand J Rehabil Med* **7**:13−31, 1991.
18. Yang CH, Luo CH, Yang CH, Improved measurement of grip strength through use of a pressure sensitive hand dynamometer, *Biomed Eng-App Bas C* **14**:157−163, 2002.
19. Lindeman RW, Sibert JL, Hahn JK, Hand-held windows: Towards effective 2D interaction in immersivevirtual environments, in *IEEE Proceedings on Virtual Reality*, Houston, TX, USA, pp. 205−212, 1999.
20. Eng K, Siekierka E, Pyk P, Chevrier E, Hauser Y, Cameirao M *et al*, Interactive visuo-motor therapy system for stroke rehabilitation, *Med Biol Eng Comput* **45**(9):901−907, 2007.
21. Ziherl J, Podobnik J, Sikic M, Munih M, Pick to place trajectories in human arm training environment, *J Tech Health Care* **17**:323−335, 2009.
22. Lang CE, Wagner JM, Edwards DF, Sahrmann SA, Dromerick AW, Recovery of Grasp versus Reach in People with Hemiparesis Poststroke, *Neurorehabil Neural Repair* **20**:444−454, 2006.
23. Mihelj M, Nef T, Riener R, A novel paradigm for patient-cooperative control of upper-limb rehabilitation robots, *Adv Robot* **21**:843−867, 2007.
24. Podobnik J, Munih M, Robot-assisted evaluation of coordination between grasp and load forces in a power grasp in humans, *Adv Robot* **20**:933−951, 2006.
25. Johansson RS, Westling G, Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip, *Exp Brain Res* **71**:59−71, 1988.
26. Mathiowetz V, Kashman N, Volland G, Weber K, Dowe M, Rogers S, Grip and pinch strength: Normative data for adults, *Arch Phys Med Rehabil* **66**:69−74, 1985.
27. Cole KJ, Age-related directional bias of fingertip force, *Exp Brain Res* **175**:285−291, 2006.
28. Cole KJ, Rotella DL, Harper JG, Mechanisms for age-related changes of fingertip forces during precision gripping and lifting in adults, *J Neurosci* **19**:3238−3247, 1999.