
Chapter 2

Human sensorimotor control of manipulation

This chapter presents the neuroscience studies that support and inspire the contact-based robot manipulation framework presented through this thesis. Firstly, a review of the existing human grasping neuroscience experiments is shown. Secondly, the methodology, results and conclusions of some selected studies are detailed. Finally, using the conclusions extracted from the presented studies, the required building blocks for a human inspired manipulation system are outlined and mapped to the components of the contact based robotic framework.

2.1 Motivation

As discussed in the introduction, nature can be a helpful source of inspiration to provide solutions for current engineering problems. Regarding robot object manipulation, a possible solution could be to mimic how humans or great primates address those tasks. Unfortunately, so far there is not enough evidence about how the brain works and how the manipulation is performed at a sensorimotor level.

However, there is a wide variety of neuroscience studies carried out on humans, that can provide some ideas on how human manipulation works. In this thesis we have used the ideas provided by those theories, to structure and implement a system capable of manipulate robustly known and unknown objects, in unstructured environments and adapt to unexpected events.

Apart from the study of human manipulation, there is another important component required: the visual perception that allows humans to detect, localize and recognize objects in order to obtain enough information to generate grasping plans and allow physical interaction. This chapter focuses on sensorimotor control for manipulation, object detection and recognition is discussed in Chapter 8.

2.2 Neuroscience of human grasping

There is a huge amount of research on human manipulation. The studies are usually based on a set of experiments conducted on a reduced number of subjects. Generally the experimental setup consists of an object on a table in front of the subject (see Fig. 2.1 Left), who has to grasp it, manipulate it and place it again on the table. During the different tests, object properties, environment, or perceptual conditions are often altered to observe the effect those alterations have on the task performance. It is also common to ask the subjects to perform the grasp in a specific way or add some constraints to the manipulation process (e.g. do not tilt the object, use index and thumb).

The data recorded depends mainly on the target of the study and can be gathered instrumenting the subject (fMRI, micro-neurography, data gloves), instrumenting the object (markers, force sensors, pressure sensors, distance sensors), instrumenting the environment (cameras, sensors on the table) or by a combination of them (gaze trackers, motion capture systems). Finally the data is analysed, discussed and the conclusions are provided.

The experiments can be classified in four different categories regarding their motivation and study goal: visual perception, motion and grasp planning, physical interaction and grasping. The next subsections provide examples of experiments of each type available in the literature and review papers and books where more details can be found.

2.2.1 Visual perception experiments

One subset of the neuroscience experiments available in the literature, is focused to the study of how visual input is processed in order to enable grasping and dexterous manipulation.

[Singhal et al., 2007] performed a series of manipulation experiments to determine the influence of visual feedback and memory while manipulating objects. After memorizing a list of paired words, the subjects were asked to grasp an object while having to recall a pair from the list. The experiment was repeated asking the subjects to perform a delayed grasp (i.e. look at the target object and grasp it without visual feedback). The results suggest that there is interference between the recall and grasp task supporting that the processing of stored perceptions information is used for the grasping tasks.

A review of experiments related to the neuroscience of visual-based manipulation can be found in [Chinellato and Del Pobil, 2009]. The review introduces the experiments performed on humans and presents a functional model of the brain that is suitable to be implemented on a robot. This studies are reviewed and used in Chapter 8 as the foundations of the implemented visual system.

2.2.2 Motion and grasp planning experiments

The trajectory that the arm follows when approaching an object is not random neither naïve. The motion planning performed by humans is also studied by neuroscientists because it can be influenced by many factors: environment, object a priori knowledge, subsequent actions, additional constraints or available sensor feedback. The influence of the subsequent actions was studied by [Hesse and Deubel, 2010], they concluded that the subsequent actions have an important influence if the task is easy. On the other hand, if the task is complex the planning does not take into consideration the subsequent actions.

Despite the arm motion planning, the contact points of the finger with the object are also planned before the grasp is executed. There are also many factors that can influence the selection of contact points such as the object position, object shape, center of mass and task. [Gilster et al., 2012] performed experiments to determine the influence of shape when allowing the subjects to use all the fingers, in the introduction they provide a review of the different experiments and the elements that influence human grasp planning.

2.2.3 Grasping experiments

In order to study how humans grasp objects, [Santello et al., 1998] performed an experiment that involved subjects virtually grasping objects of different shapes, the joint angles of the hand were recorded using a data glove. Analysing the results, they noticed that most of the grasps were similar, a Principal Component Analysis (PCA) showed that almost all the variation was accounted by the first two components. This hand synergies were later evolved and implemented as a control software for robotic hands [Ciocarlie and Allen, 2009] and implemented using hardware mechanisms on a real robot hand [Catalano et al., 2012].

In another set of experiments, [Schettino et al., 2003] observed and characterized the evolution of specific hand configurations during the reach-to-grasp movement and their modulation by different amounts of visual feedback. Their results indicate the presence of early mechanisms of hand preshaping dependent on object shape, regardless of visual feedback availability, as well as late “corrective” mechanisms which are thought to be dependent on the availability of vision. For a more detailed review about neuroscience of human grasping refer to [Castiello, 2005]. A detailed analysis of the human hand and how the experimental findings are applied to robotics is detailed in the book edited by [Balasubramanian and Santos, 2014].

2.2.4 Physical interaction experiments

The experiments classified in this group intend to understand how humans interact with objects and what are the internal mechanisms used at the sensorimotor control level. In

a seminal work, [Johansson and Westling, 1984] performed a set of grasping experiments with an instrumented object and used the results to sketch the sensorimotor control of human manipulation. Those experiments were later repeated with some variations (sensors, object shape and texture) to research in the same direction and take advantage of new technologies [Johansson et al., 2001].

Human sensorimotor control of grasping has been deeply studied, for further details, parts I and II of [Nowak and Hermsdörfer, 2009] provide details about experimental methodologies, a review of the experiments performed on humans and the theories derived from the experimental results.

In this thesis we focus on physical interaction, thus the experiments and theories we have used to inspire our work are extracted from the physical interaction experiments. Nevertheless, to have a fully autonomous manipulation system, it is necessary to determine object position and properties. To develop the visual pipeline we have also taken inspiration from the neuroscience studies. The experiments and the development of the visual perception system is discussed in Chapter 8.

2.3 Human manipulation experiments

In this section, the human physical interaction experiments used to inspire the work of this thesis, are detailed and their results and conclusions are presented. In the next section, the conclusions and the resulting ideas extracted, are used to determine the building blocks that are required to build a complete autonomous manipulation system.

The experimental setup is similar among all the experiments. It consists of a table in front of the subject with the target object to be grasped on it, see Fig. 2.1. The object is instrumented with force sensors and its *position*, *grip force* and *load force* are recorded. Usually, during the experiments, the *slip force* is calculated asking the subjects to release slowly the object until it slips. The difference between the *slip force* and the *grip force* is called *safety margin*. The details of one of the devices and its components are shown in Fig. 2.2.

2.3.1 Grasping an instrumented small object

In this experiment 9 subjects were asked to grasp the instrumented object shown in Fig. 2.2, lift it about two centimetres, hold it for 10 seconds and replace it on the table [Johansson and Westling, 1984], Fig. 2.3 depicts the action sequence of one experiment. The variable weight of the object was set to 400g.

The subjects were asked to perform a specific pinch grasp on the object as depicted in Fig. 2.2. The lifting experiments were repeated from 32 to 48 times for each subject.

Three years later, the measurement apparatus was improved by adding a micro-neurography recording device. This technology allowed the tactile afferent signals to

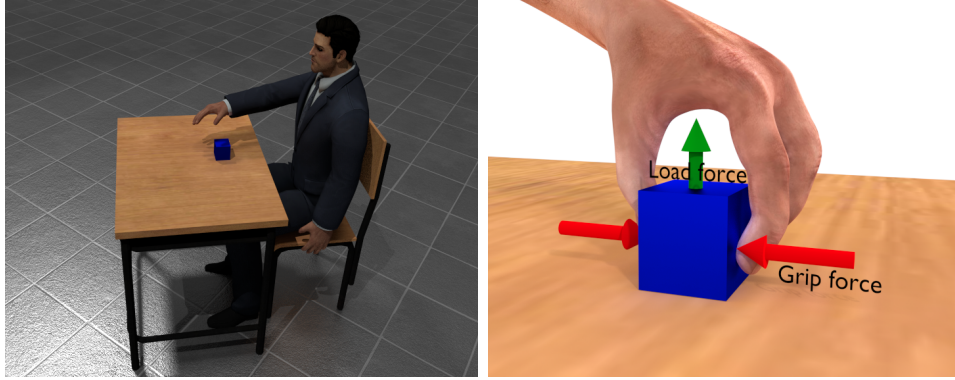


Figure 2.1: Typical experimental setup for the human precision grasping experiments: a table in front of the subject with the target object to be grasped on it. Grip and load forces are recorded together with object position. Tactile signals from the human hand are also recorded using the micro-neurography technique.

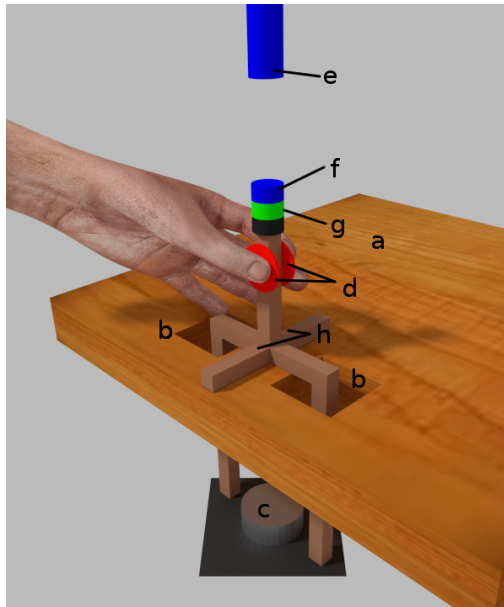


Figure 2.2: Measurement device for the grasping experiments used in [Johansson and Westling, 1984]. a) Table. b) Holes in table. c) Exchangeable weight shielded from the subject's view by the table. d) Exchangeable discs. e) Ultrasonic emitter. f) Ultrasonic receiver for vertical position measurement. g) Accelerometer. h) Strain-gauge force transducers for measurement of grip force and load force.

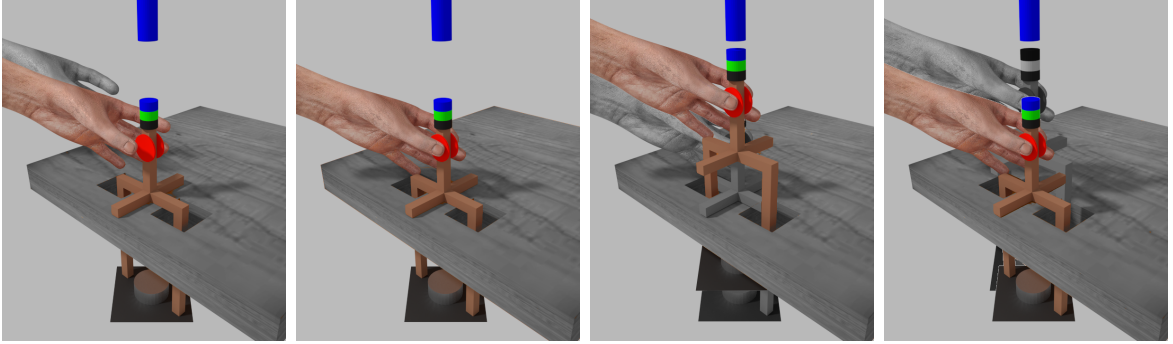


Figure 2.3: Execution steps of a grasping experiment with the instrumented object. The subject reaches and grasps the object by the red discs, lifts it about 2cm, holds for 10 seconds and replaces it on the table.

be recorded. Under the skin there are four different kinds of tactile afferents. Two of them, termed fast-adapting type I (FAI) and fast-adapting type II (FAII) respond only during dynamic phases of tissue deformation. The other two, called slowly-adapting type I (SAI) and slowly adapting type II (SAII) respond to sustained skin deformation with a graded sustained discharge [Johansson and Vallbo, 1983].

With the new technology, the experiments were repeated on 20 subjects and tactile afferent signals were recorded using the micro-neurography technique [Johansson and Westling, 1987].

Results

The averaged results of the recorded object forces and tactile afferent data are shown in Fig. 2.4. When the fingers contact the object, the grip and load forces start to increase simultaneously until the object lifts. All the subjects managed to exert grip forces that were slightly above the slip force, providing a minimal safety threshold and optimizing the time it takes to reach the desired force, reduce muscular fatigue and avoid cracking fragile objects.

The initial contact with the object is detected by the FAI and FAII afferents, but the object lift is detected only by FAII afferents. After replacing the object on the table, the object-table contact is also noticed by FAII tactile afferents and the break of contact with the object is encoded in the FAI and FAII signals.

There was a consistent delay of 0.08s between the tactile detection of the object-table contact in the replace phase, and the reduction of grip forces.

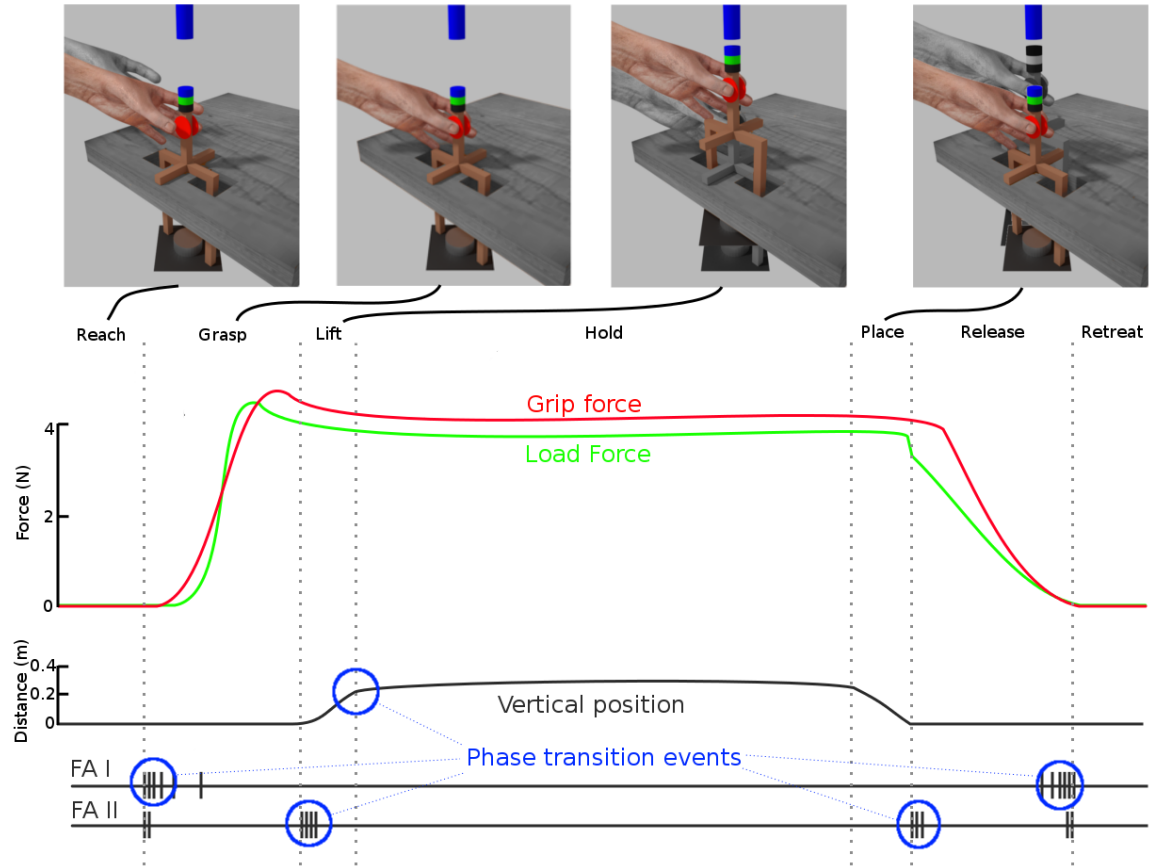


Figure 2.4: Experimental results for the instrumented box (see Fig. 2.2) grasping experiments performed by Johansson and Westling. Grip and load force directions are depicted in Fig. 2.1. Tactile signals from the human hand were also recorded using the micro-neurography technique. This diagram is a partial remake of the one in [Johansson and Flanagan, 2010] page 594, using the original data from [Johansson and Westling, 1984].

Conclusions

In 1991, using the data from these experiments, Johansson and Westling analysed the functional role of tactile signals during manipulation tasks [Johansson and Westling, 1991]. They pointed out that the transitions between phases were mainly driven by contact information and wrote: “tactile input may produce an unambiguous indication that an intended manipulative motor goal has been accomplished”.

Moreover they identified several phases during the proposed manipulation task, which were separated by sensory events. Fig. 2.4 depicts the detected tactile signals, the load and lift forces, the identified task phases and the transition events.

The identified task phases were lately coined action-phase controllers and defined as focused controllers that were bound by mechanical events. The action-phase controllers, identified for the manipulation task proposed in this experiments, are listed below:

- (a) Preload: The subject establishes the grip.
- (b) Load: The load and the grip forces increase in parallel until the load force overcomes the gravity and the object starts to move.
- (c) Transition: By wrist and/or elbow flexion the object is lifted to the intended position.
- (d) Hold: A static phase where the object is held static.
- (e) Replacement: The object is moved down and replaced on the surface.
- (f) Delay: There is a short consistent 0.08s delay until the next phase starts.
- (g) Unload: Both load and grip forces decrease in parallel until the object is released.

The reaction time to the detection of the object-table contact (delay phase) proved too fast to involve direct voluntary intervention. Hence the authors suggested that the motor commands are preprogrammed and triggered by a particular pattern of sensory information.

2.3.2 Grasping objects with unexpected friction

The first studies about the importance of frictional properties in grasp control, were performed by [Johansson and Westling, 1984]. To conduct the experiments the authors used the measurement device depicted in Fig. 2.2. To produce the change in frictional properties, the grasping pads surface was switched between silk, suede and sandpaper. The room lighting was good enough to see the target object but not to determine the material of the grasping pads. Nine right-handed healthy subjects performed a series of 32-48 trials each. The surface structure was pseudo-randomly varied between consecutive trials. The subjects were not instructed to pay attention to the grip force but to the timing and the positioning of the object in the space.

Almost a decade later, Edin et. al. performed an exhaustive set of grasping experiments targeting the frictional properties of objects [Edin et al., 1992]. Unlike the experiments by Johansson and Westling, the frictional properties of the grasping pads were heterogeneous, each pad had always different frictional properties than the other. For this experiment only sandpaper and silk were used. The frictional properties were changed randomly and recorded the lift and load forces applied independently for each finger. On a first stage 8 subjects performed 18 trials each without being able to see the object. On a second stage the experiment was repeated allowing the subjects to see the object and know in advance the type of surface that they were going to grasp on each trial. This stage analysed 29 trials on 5 subjects. A very similar measurement device to the one shown in Fig. 2.2 was used to record the experimental data.

Results

Johansson and Westling observed that the material in contact with the skin principally influenced the rate of grip force change: the more slippery the material the higher the rate. During the different tests, the subjects adapted their force to the changes in friction caused by finger sweating, indicating that they adapted to friction rather than to texture. To determine when and how the adaptation of the grip force to the surface structure took place, trials carried out subsequent to a change of the surface were analysed. The adaptation to a new surface material occurred generally around 0.1s after the object was contacted. The initial reaction to unexpected material was faster than the simple tactile reaction time: mean reaction times to tactile stimuli are over 0.15s [Lele et al., 1954]. However a comparison with the second trial on the same surface revealed that the adjustment was not complete and the first correction maintained a higher grip force, hence a greater safety margin (See Fig. 2.5).

Short-lasting slips, revealed as vibrations in the object recorded by the accelerometer, were triggering reactions between 60 and 80ms. The slips were rarely noticed by the subject and the corrections appeared to proceed in an automatic fashion without requiring the attention of the subject. The adjustment to a less slippery material is shown in Fig. 2.5 Left. The adjustment to a more slippery material is depicted in Fig. 2.5 Right.

The results of the experiments performed by Edin et. al. in 1992 confirmed those obtained by Johansson and Westling in 1984 regarding grip force adaptation to unexpected frictional properties and slip correction. Moreover Edin et. al. observed that when the frictional conditions were different for each finger, the total grip force was asymmetrically distributed among both fingers. This asymmetry enabled the safety margin to be equal for each finger. When the subjects were able to visually assert the type of material that they were about to grasp, only one out of five subjects seemed to exploit prior experience with the object with respect to the individual contact surfaces.

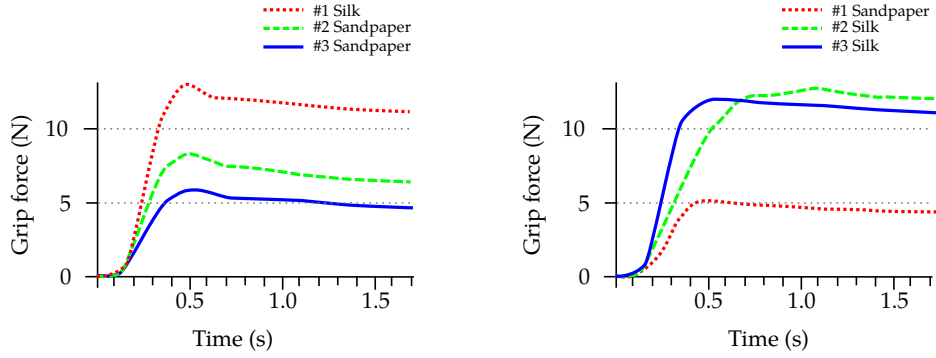


Figure 2.5: Adaptation of motor output to unexpected friction conditions. Grip forces of human grasping experiments with unexpected friction conditions. Left: Evolution of grip forces during a series of three lifts, from a slippery surface (silk) to a rough one (sandpaper). Left: Evolution of grip forces during a series of three lifts, from a rough surface (sandpaper) to a slippery one (silk). Results extracted from [Johansson and Westling, 1984].

Conclusions

The unnoticed corrective actions taken to prevent slips and adapt to different frictional properties, suggest that those reactions are directly encoded in the grasping process without requiring the subjects to be aware of them. Corrections are performed in an automatic and unattended fashion.

The adaptations of grip force are related to frictional properties detected by the tactile afferents rather than memory or other sensory cues.

The safety margin employed by all the subjects was constant among all the experiments with each subject. This suggests that it is memory-based.

The expectation from previous trials determines the initial finger forces applied when an object is lifted. Thus in the Central Nervous System (CNS) there exists a representation of a previously executed lift. This representation refers both to the object representation and to previous commands of lifting tasks [Johansson and Westling, 1991].

The task of providing a stable grasp during manipulation of objects with different shapes, weights and surface characteristics may be reduced to a problem of how to avoid accidental slips at the various digit-object contact locations. This problem seems to be solved by humans by independent digit-specific mechanisms which intermittently adjust the forces applied to an object on the basis of the frictional properties detected at each contact location.

The visual detection of the frictional properties of the object is generally not used by humans to adapt the specific finger forces.

2.3.3 Grasping objects with unexpected weight

There are several experiments that studied how prediction errors in the weight of objects affect the performance of human grasping. Some of them change the weight of the object directly [Johansson and Westling, 1984] or pull the object while it is being grasped [Cole and Abbs, 1988, Johansson et al., 1992].

During this set of experiments the subjects did not know in advance the weight of the object. Moreover, after performing several experiments they had some prior knowledge about the grasps already performed, this was exploited to change the object weight and observe the adaptation of the subjects to prediction errors. The measurement device used was the same shown in Fig. 2.2 upgraded with Force-Torque sensors between each grasping disc and the central pole. It is important to note that the weight of the object was shielded to the subject view through the holes of the table, thus there was no visual feedback available to guess about object's weight.

Results and conclusions

The results of these experiments are quite similar to the ones detailed in Section 2.3.2. The safety margin, timings and forces applied when the weight of the object was known from previous experiments, is very similar to the results from the other experiments. The corrections required to adapt to an unexpected weight are also executed in a similar fashion, the difference is that the onset of the corrective actions is triggered by the presence or absence of an expected contact event (the break of contact between the object and the table). If the object is lighter than expected, the contact event occurs before it was predicted and the correction is triggered by that mismatch. In the opposite case, the correction is triggered by the absence of a predicted event that should have already happened. The corrective actions are executed around 100ms after the mismatch is detected, suggesting that this corrective actions are also automatic and do not require the subject attention. Figure 2.6 shows two sequences of grasp and lift trials, the left sequence with object weights 800g, 200g and 200g respectively and the left sequence 400g, 800g, and 800g respectively, the adjustment of the grip force can be observed during the second trial of each sequence.

The pushing and pulling experiments show that the tactile information drives the adaptations but also the proprioceptive information can be used to cope with external forces, pointing out the importance of sensor fusion. To confirm this results, the experiments were executed also with fingertip anaesthesia, those experiments are described in Section 2.3.5.

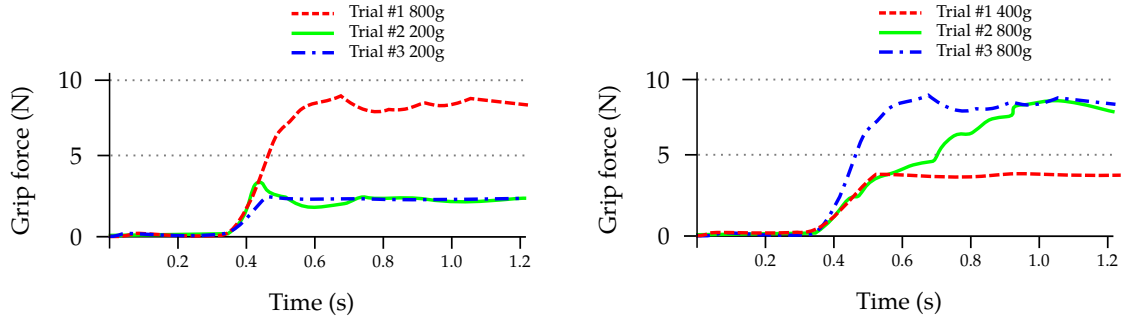


Figure 2.6: Adaptation of motor output to object weight. Grip forces for the unexpected weight experiments. Left: grip forces for a sequence of three trials with object weights 800g, 200g and 200g respectively. Right: grip forces for a sequence of three trials with object weights 400g, 800g, and 800g respectively. The initial delay in grip forces is due to the reaching phase of the experiment when the hand is moving towards the object. Results extracted from [Johansson and Westling, 1984].

From this results, the authors of the studies conclude that the corrective actions are performed in an automatic fashion by the subjects and that are triggered by mismatches of predicted contact events and actual perceived contact events.

2.3.4 Grasping objects with different shapes

To determine the importance of visual cues versus other physical interaction based sensory information, [Jenmalm and Johansson, 1997] performed a series of human grasping experiments with tapered objects, changing the angle of the graspable faces. The experiment consisted on a set of two different trial series with and without visual input. During each series, the angle of the graspable surfaces of the object was randomly changed in steps of 10° from -40° to 40° (see Fig. 2.7 Left). [Goodwin et al., 1998] performed a similar experiment but using concave and convex objects. In this case the sight of the subjects was not blocked, the concave and convex type of objects are shown in Fig. 2.7 Right. A similar device as the depicted in Fig. 2.2 to measure the grip force, load force and object position was used.

Results and conclusions

Despite the huge variation in finger force requirements, subjects automatically adapted the balance between the grip force and the load force to the object shape and maintained a constant safety margin against slips. Thus, visual cues are used to adapt force to object shape in anticipation of the force requirements imposed once the object is contacted. In the absence of tactile information, sighted subjects still adapted the force coordination

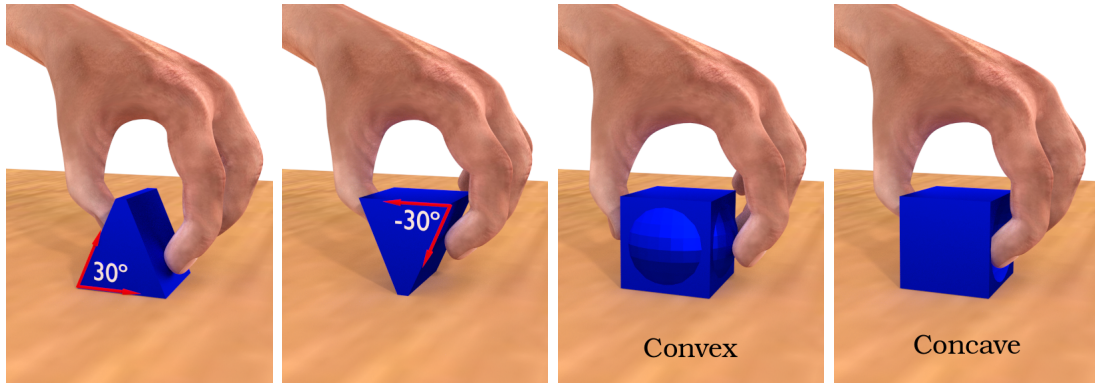


Figure 2.7: Objects used for shape based human grasping experiments. Tapered objects with angles of 30° and -30° . In the experiment the angles of the tapered object were varied in steps of 10° from -40° to 40° . Concave curved objects with radii: 20 and 40mm. Convex curved objects with radii: 20, 10 and 5mm.

to the object shape, but without vision and tactile input the performance was severely impaired. With normal digital sensibility, subjects adapted the force coordination to the shape even without vision (see Fig. 2.8).

The authors conclude that both visual and somatosensory inputs are used in conjunction with sensorimotor memories to adapt force output to the object shape automatically for grasp stability. Unlike for the frictional properties adaptation, the visual cue seems to dominate the force coordination regarding the object shape.

2.3.5 Grasping objects with fingertip anaesthesia

To assess the importance of the tactile sensory cue, there are some grasping experiments that applied anaesthesia to the fingertip tactile afferents and observed the subjects performance at grasping objects [Häger-Ross and Johansson, 1996] and reacting to external perturbations [Johansson and Westling, 1984] and to unexpected frictional properties [Edin et al., 1992].

The experiments performed by [Johansson and Westling, 1984] have been detailed in Section 2.3.1 and the experiments by [Edin et al., 1992] have been shown in Section 2.3.2. For the experiments of [Häger-Ross and Johansson, 1996], 9 healthy right handed subjects were instructed to grasp an object using different arm configurations. The object was pushed or pulled by an external force and the subjects had to keep it steady. Each subject ran 30 trials, 10 with the forearm fixed, 10 with the hand fixed (only fingers were able to move) and 10 with the whole arm free.

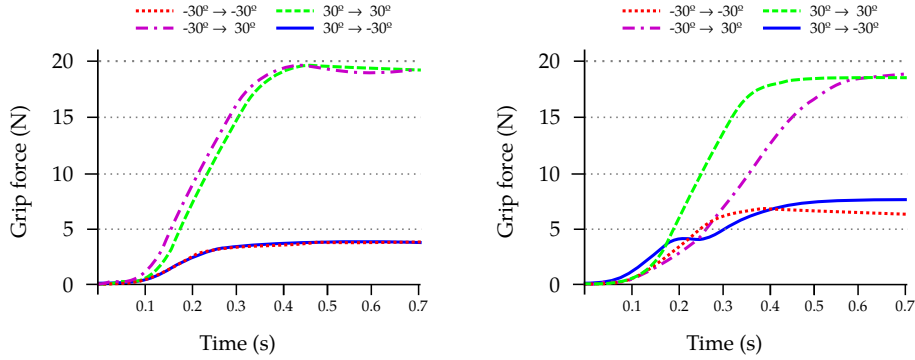


Figure 2.8: Adaptation of motor output to different object shapes. Grip forces of human grasping experiments with different object shapes. Left: with vision. Right: without vision. Results extracted from [Jenmalm and Johansson, 1997].

Results and conclusions

Although the subjects were able to grasp the objects and react to external forces, the grip force profiles were far from being optimal and the safety margins were large. The adjustments shown by the subjects to adapt to the frictional properties of the objects did not occur during finger anaesthesia. Thus the detection of the frictional properties is only tactile based.

Grip force control was dramatically reduced in the absence of tactile information. However the arm free trials showed better results than the wrist and hand fixed trials. That indicates that the proprioceptive information was used in the absence of tactile information. The performance was always worse than with the tactile input available. The authors conclude that the tactile afferents drive grip responses but when the most reliable sensory input is not available, other cues are combined to try to deal with the task as best as possible.

The subjects showed faster and more accurate reactions when the object was pulled away. It reflects preparation of a default response to the slips occurring in that direction. Reaction times when the object was pushed towards the hand were slower and the proprioceptive cue was used in combination to the tactile afferents to detect and adapt to that kind of perturbations.

2.3.6 Human corrective actions experiments

The experiments already presented, have shown that corrective actions are an important part of human grasping. Moreover their authors state that “corrective actions are highly task and phase specific and are presumably learned with the learning of the underlying action-phase controller”. However there is no clue on how the corrective

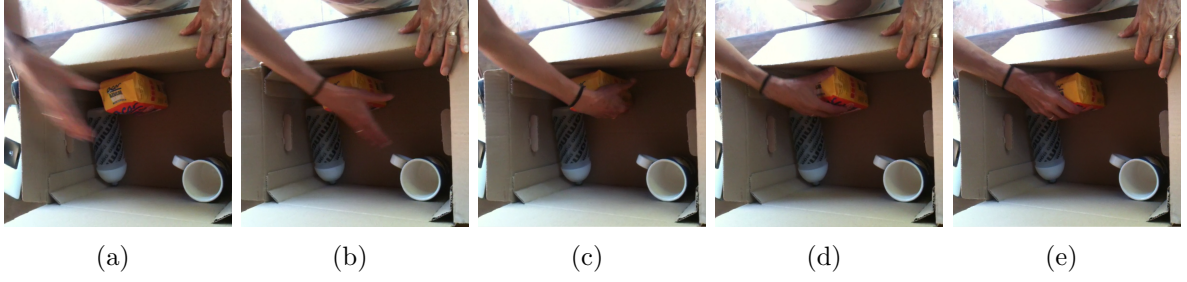


Figure 2.9: Human corrective movements extracted from the blind grasping experiment video. a) Hand moves towards the bin to touch and grasp an object. b) Initial palm contact with an object. c) Hand uses the palm contact as a pivot to rotate the wrist and obtain finger contact. d) The hand slides over the object looking for a stable grasp. e) Final stable grasp.

actions are performed. In order to take inspiration about how corrective actions were performed during the grasping phase, we conducted a simple informal experiment. The idea was to observe how humans perform corrective movements to extract ideas for an implementation on a robotic platform.

The informal experiment consisted of a box full of unknown objects that should be emptied by the subject that was standing in front of the table that was supporting the box. The subjects were 1 male and 4 females from 12 to 60 years old. The experiments were performed without any instrumentation on objects or subjects. The only data recorded was video. Figure 2.9 shows a corrective action detected after analysing the video. The figure shows an unpredicted contact and the subsequent motions to adapt, and slide over the object surface to acquire a stable grasp. Despite the inspiration taken from this informal experiments, more experiments with more subjects and proper instrumentation should be performed. Targeting the corrective movements, the mechanisms that allow humans to detect and perform corrections while executing higher level tasks could be modelled.

Results

Through the observation of the video sequences, we realized that the corrective actions taken by all of the subjects were consistent. There is a common strategy that slides over the surface of the object until free space is detected and the fingers can be opposed to grasp. It looks like the hand is reconstructing haptically the surface of the object to look for stable grasps, on the other hand it could be just a reactive strategy and the hand is adapting to the shape of the object. The results of these experiments were the inspiration for the reactive grasp controller presented in Sec. 3.3.1.

2.4 From human to robot manipulation

The experiments presented in the previous section were designed to understand how human sensorimotor control of manipulation is accomplished. After studying the results, the authors of the experiments identified several elements that contribute to human grasping:

- Action phase controllers
- Contact events
- Sensor fusion
- Contact event prediction
- Corrective actions

This five elements, together with object perception, constitute the building blocks of the work presented through this thesis. Each of the elements is detailed in the next sections of this chapter.

2.4.1 Action phase controllers

Object manipulation tasks typically involve a series of action phases in which objects are grasped, moved, brought into contact with other objects and released. These phases are usually bound by mechanical events that are subgoals of the task. Each phase accomplishes a specific goal or subgoal of the task.

A given object manipulation task can be represented as a set of sensory goals in one or more sensory modalities [Flanagan et al., 2006]. The implementation of such a plan requires the selection and execution of a corresponding sequence of basic actions to achieve the sensory goals.

The representation of the task performed by the subjects of the human grasping experiment is depicted in Fig. 2.10. The representation uses the concept of action phase controllers and the contact events to define the whole manipulation task. This concept inspired the development of the manipulation primitives paradigm. A manipulation primitive is a single reactive controller, designed to perform a specific primitive action on a particular embodiment. The manipulation primitive paradigm is detailed in Chapter 3.

2.4.2 Contact events

Contact events encode the making and breaking of contact between either the fingertips and the grasped object or the object in hand and another object or surface. The contact events provide information related to the functional goals of successive action phases. They have a crucial role in the sensorimotor control of manipulation.

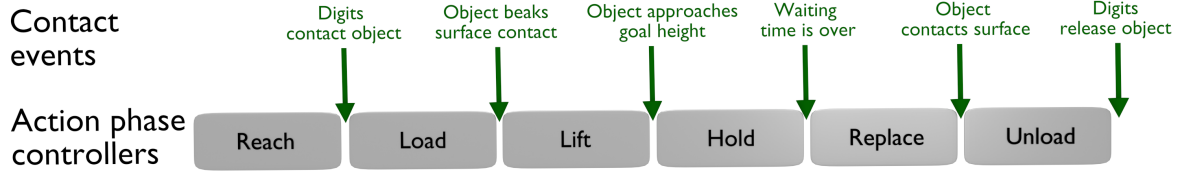


Figure 2.10: Action phase controllers used for the human grasping experiments, consisting on grasping, lifting and replacing the test object on the supporting surface. Arrows represent the event that triggers the transition from one action phase to the next one.

Contact events contribution to sensorimotor control of human manipulation is threefold. First, by comparing actual and predicted contact events, the task can be monitored and, if prediction errors arise, trigger corrective movements to respond to the unexpected events accordingly. Second, contact events give rise to salient sensory signals, they provide an opportunity for sensorimotor integration and sensor fusion. Third, the predicted consequences of contact events can directly furnish initial state information for subsequent phases of the manipulation tasks, this enables smooth transitions between different phase controllers [Johansson and Flanagan, 2010].

2.4.3 Sensor fusion

Contact events could be detected using many sensory cues, vision, force, touch or even audio. Moreover, the contact events can also be inferred on other sensory cues such as vision or proprioception. Despite the use of many different sensory cues, contact events provide a good opportunity for sensor integration, providing a common stimulus to be matched in all the perceptual modalities. The mechanisms used for contact event detection and sensor fusion are detailed in Chapter 4.

2.4.4 Contact event prediction

In object manipulation the brain not only forms action plans in terms of desired subgoals but also predicts sensory events that signify goal attainment in conjunction with the generation of motor commands, see Fig 2.11. By comparing predicted sensory events with the actual sensory events, the motor system can monitor task progression and adjust subsequent motor commands if errors are detected. The implementation of a contact event prediction engine is discussed in Chapter 5.

Contact events can function as sensorimotor control points in both actors and observers. Sensations caused by our own actions are attenuated to increase the salience of sensations with an external cause. Such perceptual cancellation could explain why we cannot tickle ourselves and why externally imposed constant forces applied to the fingertip are

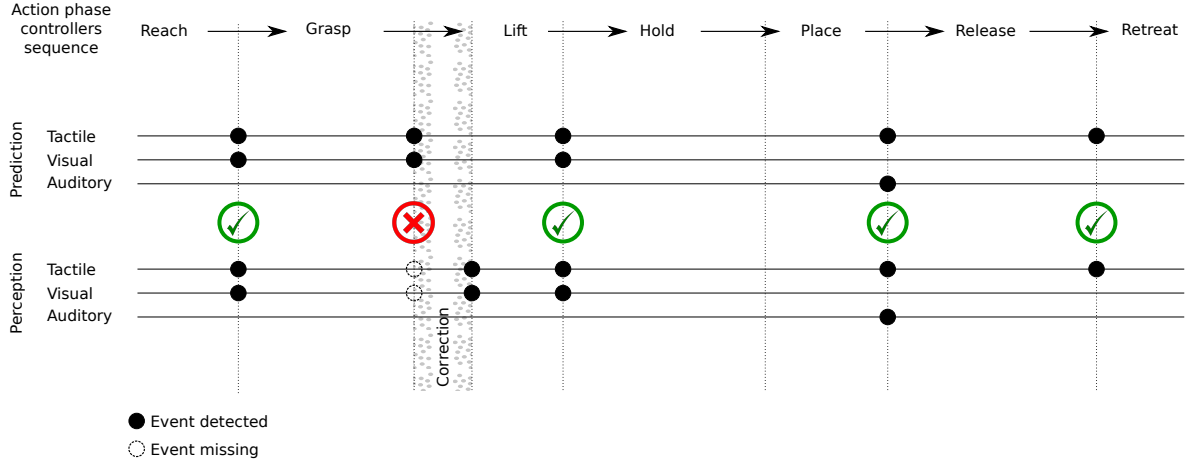


Figure 2.11: Contact events are predicted, and the actual sensory input is compared with the predictions. Prediction errors trigger corrective actions. The figure shows the response of the sensors and the predictions on each sensory cue. There is a prediction error, the contact between the object and the surface does not break when it was predicted, in this case the correction only consists on increasing the load force until the object lifts off and the expected events are detected.

perceived as more intense than the same forces applied by ourselves. Perceptual attenuation is linked to specific contact events arising from movement rather than the movement itself, [Flanagan et al., 2006].

2.4.5 Corrective actions

The resulting mismatch between the expected sensory event and the perceived sensor signals triggers a learned corrective action pattern that depends on the action phase controller and that is learned together with the learning process of the action controller. Moreover, it leads to the updating of the representation of the object properties in memory. Thus in this situation the sensorimotor system reacts quickly to both the presence of an unexpected contact event and the absence of an expected sensory event. In the presence of misleading cues, updating might require repeated action executions or movements of the target object, [Johansson and Flanagan, 2008].

As suggested by the fast reaction times in humans, the adaptation is encoded in the controller itself. All the manipulation primitives implemented in Chapter 3, are able to detect, react and adapt to unexpected sensory inputs performing corrective movements. However, there are some mismatches that should require a higher level response, such as replanning or reasoning. This can be modelled by a hierarchical corrective action schema which is part of the future work of this thesis.

2.5 Conclusions

This chapter presented the neuroscience experiments and theories that are used as the foundations of the contact based robot manipulation system presented in this thesis.

Starting from the huge number of experiments performed by the neuroscience community regarding human grasping and manipulation, we have classified the different types of experiments, selecting those suitable to provide inspiration for the implementation of a robot manipulation framework. Motivated by the lack of experimentation related to corrective movements, we have conducted an informal experiment to take inspiration about corrections in order to provide ideas for the implementation of such movements in a robotic setup. However, more experimentation on that direction should be conducted in order to provide better models and more details about how human corrective movements are performed. The results could be used to enhance the computational models that are used on the presented framework.

After analysing the results of the reviewed experiments, we have highlighted the importance of contact detection and contact events during human manipulation. Thus, we have focused our development on a contact based manipulation framework. Moreover, the building blocks of the framework were identified. Each of them is detailed in a chapter of this thesis where they are implemented and validated on different robotic platforms.

Although from the neuroscience experiments we were able to extract the main components necessary to implement a manipulation system, the results of the experiments analysed do not provide any hints or guidelines about how to implement them. Whether there is a set of latent abilities (action-phase controllers) that are refined during the development of the subject or everything is learned from scratch is an unknown. In this thesis we have implemented each building block without using a learning approach. However, learning techniques can be applied for the implementation of manipulation based controllers as discussed in Chapter 3 and also for prediction as discussed in Chapter 5.

