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Touch-Triggered Protective Reflexes for Safer Robots

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Abstract. Covering robots with a skin-like sensor can enable a range of skills that will improve human-robot interaction (HRI) both in terms of safety and communication. This position paper presents a series of concepts and problems related to developing middleware technologies to support robot skin. We define middleware as generic tactile skills that will be useful to the HRI community independent of application area and focus in particular on touch-triggered protective reflexes that can make HRI safer for both humans and robots. We review current literature on protective reflexes in biological systems and present the design of two experiments for capturing protective reflexes in humans during reaching and balancing.

1 Introduction

Collision detection has, together with low momentum and compliance, been identified as a main requirement for *safe robots* [15]. Collision detection is, in humans, closely related to a set of protective reflexes that translate the detected collisions into actions. The purpose of these actions is to keep both the person sensing the touch and his/her environment safe by stopping potentially dangerous movements and moving parts of the body away from potentially harmful positions. This paper presents concepts, technologies, problems and potential solutions for the realization of touch-triggered protective reflexes on humanoid robots. The reflexes are modeled on human protective reflexes and implemented using *robot skin*, a new sensor hardware technology that provides touch sensitivity for large areas of a robot body.

1.1 The ROBOSKIN Project

The ROBOSKIN project[2] is funded by the European Commission's Framework Programme 7 (FP7) and its activities are centered around new sensor technologies that can cover large areas of a robot's body with a touch sensitive material, i.e., *robot skin*. The activities of the ROBOSKIN project span a range of levels from sensor hardware to application specific skills. The project studies hardware for sensing not only the force and location of touch, but also the direction of the force and other non-touch phenomena such as heat and proximity. The ROBOSKIN project is also developing a level of problem domain and robot platform independent middleware such as protective reflexes and touch recognition and production skills. Finally, the ROBOSKIN project will study the application of robot skin technology in several domains, including programming by demonstration [5] and HRI for therapeutic play [9]. This paper focuses in particular on the protective reflexes activities of the ROBOSKIN project.

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[2] The ROBOSKIN project web site can be found at http://www.roboskin.eu.

2 Tactile Sensor Technology

Human skin has a wide range of sensory capabilities provided by different receptor cells. The sensory modalities of the skin include temperature (thermal receptors), pressure (e.g., Ruffini corpuscles), vibration (Meissners and Pacinian corpuscle end-organs) and pain (nociceptors) [7]. An illustration of the human skin with its most common receptor cells is provided in Figure 1.

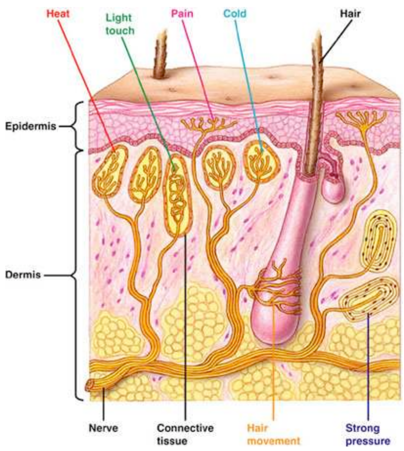

Figure 1. The different sensory receptors embedded in the human skin, from the University of Miami (http://www.bio.miami.edu/ cmallery/bil150.htm).

Our work will provide study protective reflexes. These can be triggered by both thermal receptors and mechanoreceptors. However, the first generation robot skin prototype will only have pressure sensory capabilities. Historically a wide range of sensory technologies has been studied in the context of robot tactile sensing including microelectromechanical systems [3], force-sensitive resistors (FSRs) [17] and a quantum tunneling compound [4]. Dahiya *et al*. have published a comprehensive review of human sensory capabilities and potential technologies for robot skin [8]. It is an explicit objective for the ROBOSKIN project to develop robot skin technology further, including an integration of multiple sensory modalities into a single sensor. The initial work, however, will be focused on a new sensor technology that provides purely tactile feedback from large areas of the body.

A picture of the initial prototype skin sensor that will be used for the ROBOSKIN work is given in figure 2. Each of the golden disks on the interconnected triangular base plates is an individual touch sensor. Cannatta *et al*. [6] have presented this technology in detail.

Figure 2. The first robot skin prototype fitted on a human hand.

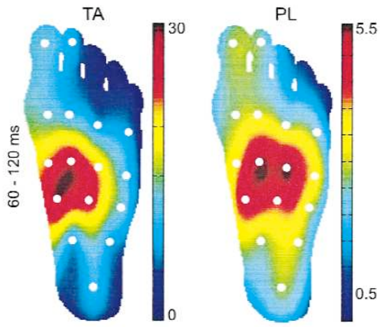

Figure 3. The receptive fields of the tibialis anterior (TA) and peroneus longus (PL) muscles, from Andersen *et al*. [2]

3 Human Protective Reflexes

The simplest level of sensor-motor integration in biological entities consists of reflex actions [7]. The simplest human reflex, the *monosynaptic stretch reflex*, relies on a single synaptic connection, within the spinal chord, between the receptor cells sensing the stimulus and the effector cells producing the response. The directness of this connection allows humans to respond to increases in muscle stretch within 5o milliseconds. Increasing the intensity of the reflex stimulus reduces the response time and increases the duration and amplitude in the response. The monosynaptic stretch reflex plays an important role in balance and posture control.

All human reflexes, other than the monosynaptic stretch reflex, are *polysynaptic*, i.e., the neural pathway or *arc*, between the sensors and effectors contain multiple synapses. Polysynaptic reflexes are subject to inhibition from the brain, e.g., the reflexive extension of the fingers as a response to painful stimuli can be inhibited when carrying a hot casserole. Among the simpler polysynaptic reflexes we find the *nociceptive withdrawal reflex*, i.e., the withdrawal of a limb as a response to *noxious* or painful stimulus produced by mechanical, thermal or chemical stimulation. This is the reflex we aim to study and reproduce in this work. Other polysynaptic reflexes are more complex and include other sensory modalities, e.g., the *pupilary light reflex* that reduces the diameter of the pupil in response to light intensity and the *primitive grasp reflex* that closes a baby's hand when something touches their palm.

3.1 Reflex Receptive Fields

Research on the *cutaneous* or skin-related nociceptive withdrawal reflex (NWR) has shown that a reflex has a related *reflex receptive field* (RRF) and that each RRF controls only a single or small group of muscles [22]. As the stimuli moves towards the edge of the RRF, the response is reduced. Further research on RRFs has shown that such fields are also clearly observable in humans [2]. Two RRFs on the sole of the human foot are illustrated in Figure 3.

The two RRFs illustrated in Figure 3 control two muscles in the leg, the tibialis anterior and the peroneus longus. The locations of these two muscles in the human leg are illustrated in Figure 4.

Another observed effect in relation to NWR is the increased excitability during voluntary movements compared to the excitability during static body postures [11]. Finally, research on infant humans and monkeys has shown that the ability to inhibit reflexes increases with age, allowing increased cortical control as a person matures [10].

Figure 4. The muscles activated by the RRFs in Figure 3, tibialis anterior and peroneus longus, from the UCLA online Health Encyclopedia (http://www.uclahealth.org/).

In order to implement protective reflexes on a humanoid robot, we need to map the responses produced by a range of different stimuli. From such maps we can then develop an implementable reflex model. In addition to this mapping, however, there are also still several open questions w.r.t. the basic nature of protective reflexes. The two questions we see as the most critical for the successful production of an appropriate model are:

1. Are reflexes sensitive to the force direction as well as the force magnitude of a touch?
2. Are reflexes expressed by a single dominant muscle?

We plan to address the first question experimentally, by producing appropriate stimuli and capturing the resulting response. If reflexes are force direction insensitive, it will reduce significantly the size of the problem we are modeling. As our prototype technology cannot sense force directions, it will also not be possible to implement force direction sensitive reflexes until later generations of robot skin technology become available.

The second question is more difficult to answer. Most reflexes involve multiple joints, but it is possible that only one joint is dominant while the remaining joints are only compliant so as to accommodate the movement produced by the dominant joint. Using the techniques presented by d'Avella *et al*. [12], we will evaluate motion data from human protective reflexes. The basic reflex arc may help explain muscle synergies such as those found by d'Avella *et al*. and we hope to be able to find similar synergies in human withdrawal reflexes.

4 Capturing Human Protective Reflexes

A range of methods have been used to elicit withdrawal reflexes in humanoids. These include the application of pin-pricks or heat [16], reaching with a transparent barrier [10], direct electronic stimulation of the sensory nerve [24] and electronic stimulation of the sole of the foot [23]. To capture the reflexes, a goniometer or angle-meter, is commonly used [1], measuring the reflex for a single joint.

Our work will use the Gypsy-6 mechanical full-body motion capture suit from Animazoo Ltd.[3] to capture protective reflex responses. The Gypsy-6 suit is shown in Figure 5.

Figure 5. The Gypsy-6 mechanical full-body motion capture suit, from the Animazoo web-site (http://www.animazoo.com/).

The Gypsy-6 suit allows us to measure the angle of a response at multiple joints simultaneously. Understanding how a stimuli affects a range of effectors will increase our understanding of protective reflexes and will allow us to implement such reflexes on humanoid robots. Figure 6 shows a graphical representation of motion data capture during reaching.

Figure 6. Single frame from motion captured in the reaching scenario developed for analysis of protective reflexes in humans.

[3] Further information on the Gypsy-6 motion capture suit is available from the Animazoo web-site at http://www.animazoo.com

To produce high-quality data for our models we have formalized a set of experiments over a range of parameters and scenarios. The parameters considered reflects issues such as whether the subjects are expecting to be touched and the direction of the touch force. The three main scenarios, reaching, standing and walking, have been formulated to cover situations where the expression of protective reflexes takes significantly different forms.

Two main factors differentiate the scenarios, the need to maintain balance and the need to recover from a perturbation to achieve a goal. With respect to goal orientedness, in the reaching and walking scenarios the robot is engaged in active, goal oriented behaviors when the unexpected touch takes place. This means that the perturbation produced affects the performance of those behaviors and raises questions about how to recover. In the standing scenario, on the other hand, there is no explicit active behavior and thus, no explicit need for recovery. With respect to balance maintenance, in the reaching scenario there is no need to maintain balance and perturbations do not have implications for other joints than those in the arm. In the standing and walking scenarios, on the other hand, the perturbation has consequences for several links in the kinematic chains around the touch point as the whole body posture must be moderated to avoid the robot falling over. Table 4 summarizes the different requirements of the different scenarios.

Scenario	Goal Oriented	Balance Maintenance
Reaching	Yes	No
Standing	No	Yes
Walking	Yes	Yes

Table 1. The differences in requirements for the three scenarios considered for analysis of human protective reflexes.

5 Formalizing the Reaching Experiment

When unexpected touches are experienced during reaching, the arm is generally moved quickly away from the stimuli, i.e., in the direction opposite to the side of the arm where the touch was made. We have noticed, during initial explorations that the perturbations produced in this scenario, rarely changes the configuration of the lower arm, but appears to be produced mostly by a single movement in the shoulder.

This experiment is designed to capture and measure the withdrawal reflex activated when a subject reaches for an object and encounters an unexpected and unpleasant stimulus. It also aims to capture the subsequent trajectory correction performed to successfully reach the target object. The experiment will measure the reflex reactions caused by stimulating several different locations on the arm during reaching. It is desirable to record the same reaching action both with and without a reflex reaction, as the final implementation of these reflexes on a humanoid robot will express them as a modulation of the underlying behavior.

Each trial will record the unmodulated and then the reflex-modulated actions resulting from reaching from a fixed starting point to a fixed target object and with a fixed stimulus location. These fixed locations are designed to stimulate a certain point on the subject's arm, and to allow for a consistent stimulus location in each trial across all the subjects. During one reaching trial, the subject will start from a set position and reach for a target object several times. During one of these reaching motions, a stimulus will be placed appropriately so that it will make contact with the desired area of the arm.

This will allow the natural, unmodulated action to be captured, along with the same action modulated with a reflex. In order to make the stimulus as unexpected as possible, the subject will be blindfolded during the second part of each trial when the stimulus is present. Also, there will be a random number of blindfolded reaching motions when a stimulus is not present. The subject will also wear some form of hearing protection during the second part of each trial, to prevent the subject from gaining any information about the presence of a stimulus by auditory cues.

5.1 Stimulus Locations

Six locations on the arm have been identified as being potentially interesting, as they are the most likely places that would encounter some kind of obstacle during reaching. All of these are described for the right arm, a trial involving a left-handed subject would be exactly the same except that all relative position references would be to the left, not the right.

Upper arm: For the upper arm we have identified two locations that will be stimulated during the trials:

1. **Upper arm 0 degrees** - the point midway between shoulder and elbow, on the biceps
2. **Upper arm 90 degrees** - 90 degrees to the right of location 1: the point midway between shoulder and elbow, on the outside of the arm

Lower arm: For the lower arm we have identified four further locations that will be stimulated during the trials:

3. **Lower arm 0 degrees** - the point midway between elbow and wrist, on the palm side of the lower arm
4. **Lower arm 90 degrees** - 90 degrees to the right of location 3: the point midway between elbow and wrist, on the outside of the lower arm
5. **Lower arm 180 degrees** - 90 degrees to the right of location 4: the point midway between elbow and wrist, on the same side of the lower arm as the back of the hand
6. **Lower arm 270 degrees** - 90 degrees to the right of location 5: the point midway between elbow and wrist, on the inside of the lower arm.

5.2 Experimental Setup for Reaching

Target Object: We want to measure not only the time and amplitude of the reflexes, but also the accuracy of the subject's reaching. This is because our data will be published as a protective reflex benchmark. It is not necessary for the subject to actually take or even grasp the target object, only to touch it. Therefore, the target object will be a small blackboard, approximately 15cm square, with a cross painted in the center. During the first part of each reaching trial, when the subject can see, they will be told to reach for the cross and touch it with their fingertips. The subject's fingers will be dipped in powdered chalk before each blindfolded reaching motion, allowing the end-point of the subject's reaching trajectory relative to the central cross to be recorded. This object will be held on a suitable stand with a sufficiently heavy base. A suitable stand could be made from a microphone stand, adapted with a heavier and more stable base.

Stimulus Object: The obstacle will be designed so that when encountered, it will provoke as strong a reflex reaction as possible. To achieve this, it will incorporate some kind of edge or point. The current design consists of a metal wedge, the point of which will come into contact with the subject, and incorporating an FSR to measure the force with which the stimulus was encountered by the subject. The obstacle will be held on an adjustable mechanical arm that has a sturdy base. As above, a modified microphone stand could be suitable. It will be placed so that the subject will still have an alternative path to the target object.

Starting Positions and Target Locations: For each of the stimulus locations discussed above we have formalized the experimental setup in terms of the starting position of the subject, the location of the target and the location of the stimulus.

Location 1 (upper arm 0 degrees - biceps):

- **Starting position:** Right arm held down, parallel with the body, palms facing inwards
- **Target object location:** At subject's elbow height, 10 cm away from fingertips when the lower arm is raised 90 degrees.
- **Stimulus location:** Placed close to the biceps muscle, on a mechanical arm parallel to the subject's lower arm when raised and fixed at the other end. This will allow the subject to reach the object to the left or right of the obstacle after encountering it.

Location 2 (upper arm 90 degrees outside of upper arm):

- **Starting position:** Right arm held down, parallel with the body, palms facing forwards.
- **Target object location:** At subject's shoulder height, at arm's length away.
- **Stimulus location:** Placed close to the desired stimulus location, held on a mechanical arm parallel with the shoulders. Again, this will allow the subject to reach the object to the left or right after encountering the obstacle.

Location 3 (lower arm 0 degrees palm-side of lower arm):

- **Starting position:** Right arm held down, parallel with the body, palms facing forwards.
- **Target object location:** At subject's elbow height, a little more than the length of the subject's lower arm away in front of the subject.
- **Stimulus location:** Held on a mechanical arm that is parallel with the subject's lower arm when it is raised.

Location 4 (lower arm 90 degrees - outside of lower arm):

- **Starting position:** Right arm held down, parallel with the body, palms facing inwards.
- **Target object location:** At subject's elbow height, a little more than the length of the subject's lower arm away in front of the subject.
- **Stimulus location:** Held on a mechanical arm that is parallel with the subject's lower arm when it is raised.

Location 5 (lower arm 180 degrees back of lower arm, same side as back of hand):

- **Starting position:** Right arm held down, parallel with the body, palms facing inwards
- **Target object location:** At subject's shoulder height, at arm's length away to the side of the subject
- **Stimulus location:** Similar to location 2

Location 6 (lower arm 270 degrees inside of lower arm):

- **Starting position:** Right arm held down, parallel with the body, palms facing forwards.
- **Target object location:** At subject's elbow height, at arm's length away but on the left hand side of the subject's body.
- **Stimulus location:** Close to the center line of the subject's body, a small distance in front of the subject, at elbow height.

5.3 The Complete Trial Procedure for Reaching

Each subject will be stood, wearing the motion capture suit, and with their sleeves rolled up. A target object will be placed a set distance front of them (in the appropriate position, as described above). They will then be told to touch the cross in the center of the target. This will be repeated three times, with the target in the same place. The subject will then be blindfolded, wear hearing protection, dip their fingers in powdered chalk, and be told to reach for the same target. This will again be repeated a number of times, but during one of these a stimulus will be put in the way (in the position described above). The reaching motion on which this occurs is randomly chosen to prevent any influence by the researcher on the day of the experiment. No subject has the same number for both trials. Also, the stimulus is never placed on the first blindfolded trial, to allow the blindfolded reaching accuracy to be measured The subject's starting position and the locations of the target object and stimulus vary for each trial, as described above. Also, there will be a fixed time period between each reaching movement. This is to prevent the subject from guessing any information about when the obstacle has been placed. 20 seconds should be enough time.

5.4 Further Evaluation of the Reaching Experiment

Further to this experiment, we would like to assess whether reflexes are sensitive to touch force direction and whether there is a single dominant muscle/degree of freedom that produces the perturbations. The reaching scenario is the scenario in which such effects will be most visible as it does not require the robot to maintain balance, something that could potentially blur the effect of the perturbation itself.

Another interesting element to keep an eye on during these experiments is the differences between left and right-handed people. It would also be interesting to tell the subjects to reach with different speeds, fast versus normal versus slow/cautious. With fast reaching is that the stimulus becomes stronger and it would be interesting to see what the effect on the response would be.

6 Formalizing the Balance Reflex Experiment

Unexpected touches to the upper body will, when humans are standing still, make them shift the body away from the touch point. Touches to the legs will typically produce steps away from the touch point. When the body is shifted, it is typically shaped into new, stable position. The new position, however, typically places an increased amount of stress on certain joints, i.e., the new poses are 'uncomfortable'. They require muscle activity and are difficult to maintain over a long period of time.

In this scenario we are particularly interested in the recovery from the perturbations produced. Without an active behavior to take over control, we are interested in seeing how recovery will take place and what the differences will be between recovery in this and the two other scenarios.

This experiment is designed to capture the unconscious movements performed when a human subject is pushed or poked off-balance (the balance reflex). During this experiment, each subject will be stood up in the motion-capture suit and blindfolded, and poked with a suitable stimulus in one of four locations, and with varying force. The resulting movements performed to stay upright will be recorded by the suit.

During this initial experiment into measuring balance reflexes, there will be four stimulus locations:

- **Left shoulder** a poke into the left shoulder from the side, in line with both shoulders.
- **Right shoulder** as above, for right shoulder.
- **Back** a poke into the middle of the back
- **Chest** a poke into the middle of the chest.

The Stimulus Object: The stimulus object will be based on the one used for the withdrawal reflex experiment described above, but mounted on a suitable boom.

The Complete Trial Procedure for Balancing The subject will be stood, wearing the motion capture suit, and blindfolded. They will then be poked in the appropriate location and with the appropriate force.

Further Evaluation of the Balancing Experiment It would be interesting to evaluate whether the force direction, i.e., incident angle of the stimulus with the skin, of the stimulus affect the response. Human skin can probably sense differences in force direction while the current robot skin technology cannot. It is also unclear whether we can design an experimental procedure that can produce different but consistent and accurate force direction stimuli.

Finally, it would also be interesting to note any differences for one given stimuli between those recorded on people who had that stimulus first and those who had it second. This would highlight any differences due to the subject's reactions after the first reaching measurement, e.g., location 2 is measured second on subject number 1, but third on subject number 6.

7 The Walking Experiment

The walking scenario is the most ambitious as walking is a difficult problem in its own right, made increasingly difficult by the addition of protective reflexes. Perturbations in this scenario typically include changing in posture, turning the body and stepping away from the touch point. These complex perturbations appear to require multiple forms of recovery. The natural body posture for walking must be recovered as must the orientation towards the goal the robot was heading for before the unexpected touch took place. The most interesting features of this scenario are the effects of perturbation on a goal oriented behavior that involves the whole body and also the interaction between the recovery of natural body posture and goal oriented behavior.

We have not yet formalized this experiment as we are expecting the lessons from the reaching and balance experiments to heavily influence our process for experimentation. Thus, we will wait for those lessons before investing more time in the formalization.

8 General Methodological Considerations

It is difficult to predict how much information each participant should be given about the experiment, e.g. whether to give them any forewarning at the start of the experiment that there will be an obstacle. If no warning at all is given, the reflex reaction should be more natural. However, the subject may then not continue reaching for the target, and immediately following the reflex reaction (whatever that may be), there will be some other motion, such as moving the arm completely away from the test area, gesturing at the experimenter, etc. If some warning is given, for example, by telling the subject, once blindfolded, to Continue reaching for the target object no matter what happens, then the reflex reaction could be less natural, as the subject now has some foreboding that something will happen, but then at least they will continue towards the target.

9 Representing Protective Reflexes

The purpose of our motion capture experiments is to collect data describing both unperturbed and perturbed behaviors in order to separate the motions produced by the reflexes from the motions produced by the behaviors that are active prior to the unexpected touches. From the isolated reflex data we hope to produce motions that we can simply add to ongoing motions whenever a robot encounters unexpected touches. Assuming that we can isolate and represent these reflex perturbations, questions arise as to how to represent the motion related to recovery and how to integrate these motions with the implementations of the domain specific behaviors. The integration mechanisms should make it as easy as possible to include reflexes across different problem domains and robot platforms. Our aim is to produce a platform independent library of reflexes for humanoids that can be easily integrated into existing robot behavior development frameworks [13, 21] in a way that hides the reflexes and allows roboticists to develop new robot behaviors without considering their potential effects.

9.1 Integrating Reflexes and Behavior

We have identified two distinct approaches to integrating a library of protective reflexes with higher level behaviors. First, we can integrate the reflexes at the lowest level possible, i.e., at the motor interface level where raw joint speeds and angles are specified, e.g., the YARP arm interface provided with the iCub software [13]. We call this approach *motor interface integration*. Motor interface integration has the advantage of being representation independent, leaving roboticists free to use whatever representation they think appropriate to develop the domain specific behaviors, whether this is operational space methods [18] or radial basis function neural networks [20]. A disadvantage in motor interface integration is that it becomes difficult to represent and integrate complex reflexes, e.g., the whole body posture changes observed in perturbed walking. For such reflexes, a representation level integration would be more natural, implementing reflexes using the same framework that is used to implement the walking in order to produce changes to the overall walking pattern rather than to individual joints or legs.

Representation level integration requires representation specific libraries of reflexes, e.g., a set of reflex behavior modules in a common behavior-based development framework such as iB2C [21]. Representation level integration appears better suited for expressing reflexes with general effects on complex behaviors such as walking or when whole body constraints are present such as when balance must be maintained. The apparent disadvantage to this approach is that the reflex representations would no longer be generic. The reflexes would have to be re-implemented for each representational framework in order to support relevant interaction mechanisms.

We plan to implement and compare both of these approaches to integration. It is also possible that a generic low-level representation can be found that supports quick re-implementations of reflexes in novel representational frameworks in the same way that, in programming, C libraries are relatively easy to wrap up in thin interfaces making them quickly available to new programming languages.

10 Platform Independent Reflexes

Another issue related to the general applicability of a reflex library is the expression of the captured motion on different humanoid robot platforms. Different limb dimensions, relative joint positioning, weight and motor efficiency means that motor speeds or joint angles cannot be transferred directly between platforms. Several solutions to this problem has been proposed. We will be looking at two in particular, a constraints-based approach that has been successfully applied in computer graphics where this problem is referred to as *retargeting* [14]. This approach allows a developer to specify space, time and frequency constraints for the target motion. The constraint-based methods have the limitation that the exact kinematics of the target physiology must be known. This is typically the case in robotics, but a more generic approach would be to learn a mapping between the physiology that produced the original motion data and the kinematics of the target humanoid robot platform. This would alleviate the need for explicit kinematics models. Another problem with a kinematics-based transfer is that differences in the dynamic models of the human origin and the humanoid target can lead to unstable behaviors [19]. We will explore whether it is possible to learn mappings between a human physiology and a humanoid target in a way that produces stable behaviors. The different humanoid platforms we consider for this work, the iCub platform developed by the RobotCub EC FP7 project, the Nao platform from Aldebaran Robotics, and the KASPAR robot developed at the University of Herfordshire, are presented in Figure 7.

Figure 7. The robot platforms considered as targets for the protective reflexes, the iCub, the Nao and KASPAR

11 Conclusions

The work presented here aims to model human protective reflexes and to implement similar capabilities on humanoid robots in a way that is as generic as possible. In order to achieve this, we will study human protective reflexes in detail. We will also evaluate a range of technologies for representing and integrating reflexes with other, domain specific behaviors. Finally, we will evaluate technologies for transferring motions between different humanoid platforms in order to produce reflex libraries that, as far as possible, are platform independent. This paper has presented initial concepts and problems, the work is planned to go on until May 2012.

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