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Bernstein's Levels of Construction of Movements Applied to Upper Limb Prosthetics

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ABSTRACT

This article addresses the neuromotor control processes underlying the use of an upper limb prosthesis. Knowledge of these processes is used to make recommendations as to how prostheses and prosthesis training should develop to advance the functionality of upper limb prostheses. Obviously, modern-day prostheses are not optimally integrated in neuromotor functioning. The current article frames the problems underlying the handling of upper limb prosthetic devices in the hierarchical levels of construction of movement as proposed by Bernstein (1996). It follows that 1) postural disturbances resulting from prosthetic use should be considered in training and in the development of prosthetic devices, 2) training should take into account that new synergies have to be learned, 3) the feedback about the state of the prosthesis should improve, and 4) the alteration between different grip patterns should be made easy and fast. We observed that many of the current innovations in the prosthetics field are in line with the aim to integrate the prosthesis in sensory-motor functioning. (*J Prosthet Orthot*. 2012;24:67–76.)

KEY INDEXING TERMS: upper limb prosthetics, prosthetic training, prosthetic hand, motor control, motor learning, pattern recognition, TMR

In daily life, people perform actions in an accurate and goal-directed manner seemingly without much effort. This apparent ease with which actions are performed hides the complexity of underlying neuromotor processes. The complexity of these processes often reveals itself when parts of the body are either impaired or, in the specific case of relevance to this article, when a part of the upper limb is missing because of an amputation or a congenital deficit. Prostheses are developed to replace missing body parts, but there is still a huge gap between the functionality of current upper limb prostheses and that of the natural body. This fact is indicated by the low levels of use of prostheses and high rejection rates.[1–6] To make suggestions about ways in which the functionality of upper limb prosthetics may be advanced and to increase our understanding of some basic requirements for prosthesis design and prosthesis training, this article outlines the properties of motor control processes. To do this, Bernstein's[7] ideas on the development of dexterity were taken as a starting point and were applied to the field of upper limb prosthetics.

The arms and hands are used for all sorts of actions. Some actions have an explicit goal, such as reaching for or picking up an object. In other actions, the hands are just used to support other behaviors, for instance, touching a wall or a table to keep one's balance. Hands are also used to communicate, for example, when hand movements are used to stress what we say. Moreover, both hands do not always have the same function when performing a task; in object manipulation, often, one hand serves as the stabilizer, whereas the other hand performs the focal act of manipulating (cf. Guiard[8] and Steele and Uomini[9]). Clearly, after an amputation, the absence of a hand can hamper many of those actions. The primary goal of providing a prosthesis for a patient is to create opportunities for action to a level that is comparable with that available to a person with intact arms or hands. A prerequisite for this is that prosthetic devices must be controlled dexterously. The present article discusses what it means for actions to be dexterous. This is taken as a starting point to formulate recommendations to improve prosthesis design and ways to train the use of prostheses. This discussion is restricted primarily to persons with acquired amputations below the elbow.

To understand what limits actions when using a prosthesis, it is necessary to sketch in broad strokes the properties of prostheses before addressing what makes it so difficult to

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perform dexterous actions with them. Upper limb prostheses can be categorized into three classes: cosmetic, passive, and active prostheses. Cosmetic prostheses serve mainly cosmetic purposes and lack movable parts. Passive prostheses have parts that are movable by sound body parts or the environment. Both cosmetic and passive prostheses can be used to fixate objects or to support other actions, and as such, they function as an extension of the residual limb. However, neither type of prosthesis requires a control signal of any kind, and hence, they will not be considered further here. Active prostheses have parts that can move based on some control signal. Over the years, a wide range of control systems have been explored and developed,[6,10,11] but most commercially available prostheses are controlled via body movements or from myoelectric signals.* Hence, these are the types of prostheses we concentrate on.

In a body-powered prosthesis, the terminal device is controlled through a harness around the shoulder contralateral to the arm that is amputated. Depending on the design of the harness and the prosthesis, movement of the upper arm, shoulder, and trunk translates into opening or closing of the prosthetic hand or gripper. More precisely, the harness around the contralateral shoulder acts as an anchor point for one end of the control cable that connects the harness to the prosthetic hand. Movements of the shoulders (i.e., protraction, abduction, and anteflexion) are used to pull the cable. These movements control the opening or the closing of a gripper or the tripod grip of a prosthetic hand (see Smit and Plettenburg[12] for a body-powered controlled hand with articulating fingers). The movement in the opposite direction results from a spring within the terminal device. These prosthetic hands are referred to as voluntary opening or as voluntary closing, respectively.[13–17]

In a myoelectric prosthesis, electric motors control its motions around joints such as the wrist, as well as the movements of the digits. These motors are controlled through myosignals produced by muscles in unaffected parts of the body or residual musculature in the residuum. For a long time, most myoelectric prostheses could only perform a tripod grip[10,18,19] (but for some notable exceptions, see Almström et al.,[20] Codd et al.,[21] Kyberd et al.,[22] and Nightingale[23]). Recently, several hands became commercially available in which all the digits can be flexed and extended, the so-called multi-articulated hands, so that a range of grip types is available to the user. About 5 years ago, Touch Bionics presented the iLIMB hand, in which all fingers could flex and extend around multiple joints and the thumb could be positioned in different orientations to the fingers. More recently, the improved version of the iLIMB has been presented, and also, RSL Steeper has released a multiarticulated hand (BeBionic). Otto Bock has released the Michelangelo hand that can produce multiple grip types. Importantly though, the number of myosites from which this larger range of grip types are controlled has not increased in any clinically available prosthesis. In sum, this brief sketch gives an indication of the important characteristics of the available upper limb prostheses.

*Myoelectric prostheses basically fall in the category of externally powered prosthesis, where the movement of the prosthesis results from the activation of an electric motor or from pneumatic power. However, because nowadays most externally powered prostheses are myoelectric prostheses, we use this as a category representing active prostheses.

PROBLEMS IN CONTROLLING A PROSTHESIS

Now that we have a general understanding of the different types of prosthetic devices and their control principles, it is appropriate to address the question of why the control of a body-powered or of a myoelectric prosthesis is so difficult. Several reasons underlie this difficulty, and here, we discuss three of the most important ones. First, as follows from the above description, the control signals of the neuromotor system necessary to perform a goal-directed action with a prosthesis differ from control signals used to perform an action with an intact limb. Specifically, muscles that developed over evolution for a certain function are used for a different function when controlling a prosthesis, and therefore, prosthetic control is nonintuitive. For instance, to control a body-powered hand, shoulder and trunk muscles are used. Moreover, with body-powered prostheses, friction losses in the control cable and the mechanism of the terminal device are responsible for blurring the relation between control movement and movement of the end-effector.[16,17,24,25] With myoelectric prostheses, the relation between control and effect is even more indirect because the myosignal is typically smoothed and averaged over a time window to determine whether the signal exceeds a threshold. These treatments of the signal cost time, which the user experiences as a delay between control and effect. Moreover, the transduction of the myosignals is affected by factors such as sweat, fatigue, and pressure on the electrode. This means that the relation between control signal and end-effector movement changes in an unpredictable way over the day and in different situations. The combined effects of delay and uncertainty introduce demonstrable and significant control challenges to the user.[26] In short, controlling a prosthesis is fundamentally different from controlling our natural body, and thus, it is definitely a skill that needs training.

Second, the sensory feedback that prostheses provide is limited, in some cases severely, when compared with the sensory feedback that the neuromotor system receives in natural actions. Note that appropriate sensory feedback is a primary prerequisite to perform dexterous actions. Of the main sources of sensory feedback that are important in natural actions, proprioception (i.e., muscle sense) and tactile feedback do not exist in a prosthesis. Proprioception is the sensory basis for fast, subconscious, corrective movements to reach the goal. Tactile sensors pick up shear stress on the skin, among other things. In a body-powered prosthesis, muscles acting on the harness produce the forces and displacements needed to operate the terminal device. Proprioceptive sensors in the active muscles and tactile sensors in the skin covered by the harness pick up these forces and displacements. Hence, with this type of prosthesis, direct feedback about the prosthetic hand is possible. Importantly, reacting to proprioceptive feedback is fast because it operates through fast spinal feedback loops. With a myoelectric prosthesis, no proprioceptive feedback about hand opening is possible and the tactile feedback is limited. Tactile feedback sources are feedback from the skin deformations in the socket and feedback from vibrations of the socket acting on the residual limb. Perhaps, auditory feedback from the sound of the electric motor can be used. It is extremely challenging to perceive the magnitude of hand opening or the grip force exerted on an object in this way, and most users report difficulty with this aspect.[2] Therefore, a user of a myoelectric prosthesis has to rely primarily on vision to control hand opening. The main problem with this is that vision is rather slow compared with proprioception because the use of vision requires cortical involvement that takes longer than spinal feedback loops. Furthermore, if the user is relying solely on vision, then the actions have to be performed within view, making it nearly impossible to perform an accurate action above the head or behind the back. Together, these limitations on the availability of feedback during prosthetic use result in a prosthesis that is hard to control.

Third, possibilities for movement in prosthetic hands differ from that in the natural hand. These possibilities for movement are called degrees of freedom. Prosthetic hands have fewer joints than the natural hand does because most body-powered and myoelectric hands perform only a tripod grip. More importantly, the degrees of freedom that can be actively controlled with a prosthesis differ from those of a sound hand. Most prosthetic hands have only 1 degree of freedom that must be controlled, that is, opening and closing of the device. In body-powered hands, usually, only one direction of motion is controlled voluntarily. Recent multiarticulated hands seem to improve the reliability of the grasp of an object compared with that of the traditional tripod grip (cf. Van der Niet et al.[27]). However, the control exercised by the user is still only to open and close the hand, once the grasp is selected. For instance, in the lateral grip, the fingers form a fist and the thumb opens and closes toward the medial phalanx of the index finger. In a power grip, all digits open and close, but this is the only degree of freedom of control in this mode. This is different from the function of a natural hand because, for instance, a natural hand can open and close while at the same time spreading (i.e., abducting) the fingers. Depending on task requirements, the opening and spreading movement can be done in a coupled fashion or independently, demonstrating independent control of at least two independent degrees of freedom in terms of control. The currently available prosthetic hands do not allow for controlling these two features independently. Clearly, the few degrees of freedom that can be controlled in prosthetic hands severely limit the use of prostheses.

In sum, the main differences regarding neuromotor control between a prosthesis and the natural body are that 1) the signal that controls a prosthesis differs from the control signal that produces that movement in a natural limb; 2) prosthetic users have to rely on different, slower, and limited feedback loops; and 3) the number of controllable degrees of freedom in prostheses differ from that in natural limbs. These limitations pose serious challenges to a user who wants to perform dexterous actions with the prosthesis. Therefore, the ultimate goal of designers, clinicians, and researchers in the field is to deliver a prosthesis that, with proper training, can be used as dexterously as possible. The current article aims to make recommendations as to the directions in which those active in the field could search for routes to improve upper limb prostheses and their use. These recommendations are based on the idea that to perform dexterous actions, the prosthesis should be designed in such a way that it is easily integrated into our perception-action loops and a training protocol should be provided that aims to facilitate this integration. Therefore, in the following, we discuss what it means for the neuromotor system to learn to control an upper limb prosthetic device. This discussion will start from Bernstein's (Russian original from 1947, published in English in 1996[7]) insightful exposition on the hierarchical levels for the control of movement.

LEVELS OF CONSTRUCTION OF MOVEMENT

Without any doubt, Bernstein is among the most influential thinkers in the domain of motor control of the last century (cf. Latash and Latash[28] and Whiting[29]). He took the evolution of the neural system as a starting point to distinguish four levels of control of human movement. Each level was hypothesized to control a different class of movements. These levels were hierarchically organized, with each new level emerging on top of the existing levels. Each new level emerged from evolutionary pressures requiring a new class of movement. More specifically, based on new challenges in the environment, new actions had to evolve to meet these challenges. These newly evolved actions were accompanied by new sorts of sensory feedback. Based on the interplay between the newly emerged actions and the accompanying sensory feedback, new neural brain structures evolved. These new neural structures accounted for a new class of movements and as such represented a new level of construction of movement. Bernstein stressed that in evolution, motor function and sensory function developed mutually, which indicates that to him, motor learning takes place in the interplay between perception and action. This implies that improving prosthetic functioning requires taking into account the motor side as well as the perceptual side.

For Bernstein, the essence of motor control was to overcome the redundant degrees of freedom in the neuromotor system (cf. Whiting[29]). He argued that motor coordination is the turning of these redundant degrees of freedom into controllable systems. For Bernstein, the coordination of movements is an active process in which the best solution to control the superfluous degrees of freedom has to be found. This notion of activity is deeply embedded in Bernstein's view on motor control, as becomes clear from the fact that he denoted the levels of motor control as levels of construction of movements. In addition, his definition of dexterity clearly shows this: "*Dexterity is the ability to find a motor solution for any external situation, that is, to adequately solve any emerging motor problem correctly* (i.e., adequately and accurately), *quickly* (with respect to both decision making and achieving a correct result), *rationally* (i.e., expediently and economically), *and resourcefully* (i.e., quick-wittedly and initiatively)" (italics in the original).[7(p228)] In Bernstein's proposal, the active processes to construct movements operate at different levels that are hierarchically organized.

The four levels Bernstein[7] distinguished in motor control were the level of tone, the level of synergy, the level of space, and the level of action. The level of tone is the lowest, and also the oldest, level of motor control. This level controls the background muscular tone that provides postural stability supporting all behaviors. The next level, the level of synergy, is the one that emerged when limbs evolved; it controls the linking together of muscle-articular groups so that the numerous muscles become controllable to perform stable and reproducible movements. According to Bernstein, sensory feedback at the level of tone and the level of synergies is based primarily on proprioception. The sensory feedback at the other two levels is primarily visually based. The level of space regulates those movements that reach their goals in the workspace surrounding the body; distances and orientations of objects must be perceived for reaching movements to be goal directed. The highest level of control is that of action, in which sequences of movements are controlled. This level of control takes care of adaptive solutions to new situations.

According to Bernstein,[7] the primary aim of training was not to optimize the performance of certain behavior or a task but to become more reliable in finding solutions for the motor problem at hand. Therefore, training should present the learner with a wide range of tasks and conditions. The skill to cope flexibly and adaptively with variations in task and environmental conditions is what Bernstein saw as dexterity. He argued that dexterity always involved two levels; that is, the higher level shows properties such as quickness, switchability, and maneuverability, and the lower level shows properties such as accuracy, submission, and coordination.[28,30] He distinguished two types of dexterity: body dexterity and hand-object dexterity. Body dexterity, where the movements and orientations of the entire body relative to the environment are organized, starts from the level of space. The level of tone is always present in movements demonstrating body dexterity. Hand-object dexterity involves the level of action. This type of dexterity reflects the ability to perform fine motor skills with the hands and fingers. The level of skill an individual is able to learn in different perceptuomotor abilities reflects his/her dexterity.

What is the contemporary evidence for these levels of construction of movement as proposed by Bernstein? With regard to the relation between structures and function, Bernstein[31] stressed that there could be no one-to-one mapping between a neural structure and the function that the structure performed. This implies that although over evolution new structures emerged, the function that these structures perform depend on the networks within which they are embedded. Bernstein[7] pointed this out when he argued that some of the functions performed at a certain level were taken over by new structures that evolved. Hence, one should not look for specific neural structures that perform the functions of each of these levels. However, neuroscience has revealed relations between functioning of neural structures and what Bernstein assumed to take place at the levels of construction of movement. To illustrate this, we provide a few examples. The level of tone as proposed by Bernstein is represented by the functioning of the tonic stretch reflex[32] (cf. Latash and Latash[28]). The notion of synergies put forth by Bernstein inspired many researchers for decades. However, in the late 1980s and early 1990s of the former century, several hypotheses originating from this idea could not be confirmed experimentally.[33,34] It took another decade before new algorithms were proposed on the basis of which cooperation between muscles, that is, muscle synergies, could be revealed. It was hypothesized that these muscle synergies act as building blocks that are combined to produce a goal-directed movement[35–38]; how these muscle synergies can be used to control prosthetic devices is discussed later. These muscle synergies are supposed to reside in the spinal cord. Motor control signals from the cortex connect to the spinal cord exploiting these synergies, which is in accordance with Bernstein's idea of the employment of lower levels by the level of space and the level of action. Moreover, the idea that control of hand movements takes place at the level of action is in agreement with the notion that the motor cortex has direct connections (i.e., monosynaptic) with hand muscles (for an overview of how motor cortex connects to muscles, see Schieber[39]). In agreement with Bernstein's proposals, the percentage of muscles that have direct connections is smaller around the wrist and decreases even further for the elbow and shoulder.[40,41] This is important for the field of prosthetics because this implies that a myoelectric hand is controlled with muscles that have far fewer direct connections with the neural sites that control the hand in the natural situation, or even none for body-powered prostheses.

According to Bernstein's[7] view on motor control and coordination, in learning to use a prosthesis, a prosthetic user has to discover how the properties of a prosthesis can be integrated with the properties of the neuromotor system to solve the motor problems in a dexterous way. To outline requirements of prosthetic design as well as requirements of prosthetic training that can improve the opportunities for a user learning to dexterously use a prosthesis, we take the levels of construction of movement as proposed by Bernstein as a starting point.

LEVELS AND PROSTHETIC USE

LEVEL OF TONE

This level of motor control is easily overlooked because it operates in the background during daily activities; it is not prominent in behaviors of the upper limbs.[7] But it should be noted that this level is active in all behaviors, which makes that it has to be taken into account when aiming to improve prosthetic use. The nature of this level makes that its direct influence on upper limb function is limited.

One aspect of prosthetic use that can be observed at this level follows from the asymmetric mass distribution of the body of a person who is missing a part of his/her upper limb on one side. This asymmetry substantially affects the periodicity of the walking pattern. Wearing a prosthesis partly reduces this asymmetry, which results in the walking becoming more symmetric and reducing the varus moment in the knee at the side at which the prosthesis is worn.[42] Thus, wearing a prosthesis makes the load on the body more in balance. As can be expected, the mass of the prosthesis and mass distribution of the device are different from those of a sound arm. This implies that the load on the postural and locomotor system will always be out of balance. Hence, to minimize the effect of the prosthesis on posture and on walking patterns, the mechanical characteristics of a prosthesis should be optimized so that it approaches that of the anatomical body. However, increasing the mass of current prostheses might put too much stress on the skin in the socket with which the prosthesis is attached to the body. Connecting the prosthesis to the body through osseointegration might change this[43] (cf. Jönsson et al.[44]). Note also that the effects of increasing mass may lead to an increased effect of postural changes on myoelectric signal transduction.[45]

The level of tone should also be taken into account when developing training programs for prosthesis use. The level of tone is involved in producing anticipatory muscle activity that counteracts the reaction forces produced by moving the upper limbs. For instance, it is well established that when lifting an arm, there is muscle activity in the muscles of the trunk and legs before the muscles of the arm are activated.[33,46–48] This muscle activity counteracts the forces and the disturbances of balance that the movement of the arm produces (see Massion[49] for an overview). Because the mechanical characteristics of a prosthesis differ from those of a sound arm, moving a prosthesis may create unexpected disturbances of balance and, thus, may require unexpected anticipatory postural adjustments. Prosthetic training should focus on making prosthetic users aware of these possible disturbances so that counteracting forces can be produced preparatory to the focal movement, probably especially in the beginning of rehabilitation.

LEVEL OF SYNERGIES

The level of synergies is an important level to consider when aiming to improve prosthesis use. The notion of synergies is widely spread in the domain of motor control. In this article, a muscle synergy is defined as a specific activation pattern across a set of muscles that are activated as a unit. To produce a movement, different synergies are linearly combined.[35,50] Much has been written about muscle synergies. They come in different flavors, with each definition having its own assumptions and decomposition method. However, a full treatise of this topic is outside the scope of this article; therefore, we refer the interested reader to a collection of relevant articles.[35,37,38,51–53] Common to all these approaches is that the activity pattern for a single muscle will usually be different for each synergy. To produce a movement, a set of synergies is combined. The resultant contraction of each muscle is the summed activation of the activity of the muscle in each of the operational synergies. The idea underlying this notion of neuromotor function is that it simplifies the control because only the parameters for each synergy have to be specified by the control system and not the activity pattern for all individual muscles.

At this level, the question becomes: What does this notion of muscle synergy imply for prosthesis control? It is important to understand that learning to use a prosthesis requires to either learn new synergies or combine the available synergies in a different manner to produce the appropriate muscle activation patterns. As mentioned before, both body-powered and myoelectric prostheses are controlled with different muscles than the muscles that control natural hand movements. Hence, this implies that for body-powered prostheses, synergies activating shoulder and trunk muscles, and in myoelectric prostheses, the synergies comprising flexors and extensors of the wrist need to be combined in new ways to control the hand. In other words, learning to control a prosthesis implies learning to activate the appropriate set of synergies and tailor their activation patterns to the task at hand. Radhakrishnan et al.[54] showed that learning new muscle activation patterns in a set of muscles can be reasonably quickly achieved, although the notion of flexibility of muscle synergies was not explicitly addressed in this article. However, there are still relatively few studies of learning new combinations of synergies (but see Ajiboye and Weir,[55] Asaka et al.,[56] and Kargo and Nitz[57]), so at the moment it is hard to be specific about their flexibility.

The idea that myosignals picked up by myoelectric prosthetic devices result from muscle synergies is in line with recent technological developments. More specifically, pattern recognition algorithms have been demonstrated that extract functionally relevant useful features from multiple muscle electromyographic signals that may be representative of muscle synergies (for recent results, see Pulliam et al.,[58] Scheme and Englehart,[59] and Simon et al.[60]). The aim is to use multiple electrodes to control more complex prosthetic hands that have a larger choice of grip patterns. An important issue with these prostheses is that they are not easily controlled with two or three myosites, the way in which most prosthetic hands with only 1 degree of freedom (i.e., opening and closing of the hand) are controlled. If a small number of myosites are used to control multiple grip patterns, then co-contraction or a specific combination of activation patterns is used to switch between grip patterns of the hand. This makes the operating of the prosthesis cognitively demanding, nonintuitive, and slow. The route that is taken to overcome these problems is to record from multiple myosites and use microprocessors to establish which grip pattern the user wants to perform (cf. Scheme and Englehart[59]). Using pattern recognition techniques, the signals of these multiple sites are classified into a category (i.e., a grip pattern). Before this classifier can be functionally used, the classifier has to be trained to associate an output pattern of the myosites to a grip pattern. [58–60] In current developments, these classifiers use regular computational algorithms developed for other applications. However, perhaps, these classifiers can be improved when they exploit the idea that muscle synergies form the basis of myosignals (cf. Ajiboye and Weir[55]). That is, the muscle synergies can be considered as underlying components composing the myosignals. Therefore, if these components are put into the classifier, then the classifier only has to learn the parameter settings that belong to the myosignals and relate these parameters to an output pattern. Note, however, that the pick up of electromyographic signals required for this method might not be fully agreeable with the methods that are currently used in prosthetic devices. At the moment, it is highly speculative whether this would work and how this could be implemented. However, exploiting muscle synergies in pattern recognition to decode the patterns of multiple myosites seems to provide an opportunity to improve control of the prosthesis. By tapping into existing synergy patterns, it may also increase the rate at which people can learn to use a prosthesis.

LEVEL OF SPACE

Goal-directed reaching and grasping are controlled at the level of space. Reaching and grasping are among the most important functions of prostheses (cf. Van Lunteren et al.[61]), as these behaviors allow users to interact with objects in their surrounding world. When picking up an object, coordination is required between the reach (the transport of the hand to the object) and the grasp (opening and closing of the hand). Some basic problems with prosthesis can be readily observed in prehensile patterns when they are used to grasp an object. Comparison of prehension with a prosthesis with that of a sound hand shows some specific deviations in the reaching and grasping, found in both body-powered and myoelectric prostheses: 1) prehension with a prosthesis takes longer and has a relatively long deceleration phase of the reach, 2) the onset and termination of reaching and grasping do not occur at the same instance, and 3) the grasp profile shows a plateau phase.[62–64] These deviations of prosthetic prehensile patterns indicate that grasping is not fluent, as it is in sound grasping; it seems that prosthetic grasping is chunked into a series of submovements where hand opening and hand closing are decoupled. Probably, with body-powered prostheses, these deviations in the prehensile patterns stem from the cable control, which makes it hard to open and close the prostheses gently (cf. Bouwsema et al.[62] and Wing and Fraser[64]). With myoelectric prostheses, these deviations seem to originate from the lack of proprioceptive feedback in the prosthesis that results in prosthetic users having to rely on vision, which is slow.[62,63] This in turn results in grasping that is chunked to get the reach and grasp coordinated.

Several routes can be followed to improve prehensile patterns, of which two are presented here. One route is that training programs are specifically designed to teach users to deal with the problems of feedback in the myoelectric prosthesis. For instance, prosthetic users can be trained where to look when learning to use a prosthesis. When performing actions in daily life, gaze behavior is mostly devoted to objects in the environment and is used to gather information about objects on which succeeding actions are focused.[65–68] Two recent studies by our groups showed that the gaze of prosthetic users differs from this natural gaze pattern. Bouwsema et al.[63] demonstrated that prosthesis users divided their gaze between the object and the prosthetic hand. The gaze patterns of six experienced prosthesis users who picked up an object indicated that reliance on visual feedback to guide the prosthesis was inversely related to the hours per week that the prosthesis was used. In another study, Sobuh[69] examined gaze behaviors over the course of learning to use a myoelectric prosthesis simulator when participants performed a task involving reaching for a juice carton, pouring water from it into a glass, and replacing the carton. In the first stages of learning to use the prosthesis, attention was devoted largely to the immediate task, such as focusing on the hand during reaching, rather than assisting in planning subsequent actions in the task. Moreover, gaze was also found to be rather erratic. With practice, moderate improvements in both these aspects were observed. These studies suggest that users of myoelectric prostheses rely on visual feedback to control their prostheses, which seems particularly important in the early stages of learning. These findings seem to support our interpretation that the chunking of reaching and grasping in prehension with a myoelectric prosthesis stems from a lack of feedback. Obviously, training programs need to incorporate this. Hence, our future research is dedicated to developing tasks to be used and suggestions to be given by occupational therapists to improve training.[70]

The second route to follow is to improve the sensory feedback of the prosthesis. In body-powered prostheses, the proprioceptive feedback is inherently present. Although shoulder harnesses have been used for more than 200 years, no information is available on the magnitude of force or the magnitude of displacement that provides the best proprioceptive feedback. Recently, a study has started to identify the optimal force and displacement windows in using a shoulder harness.[71] In myoelectric prostheses, as argued by Chappell,[72] the recent amelioration in possible grip types of myoelectric hands increases the need to design sensors for detecting aspects such as applied force and object slip. In a review, Chappell describes current developments in sensor technology that might be implemented in a multiarticulated prosthetic hand so that it can autonomously keep grip on an object. Applying such technologies might relieve the user from cognitively controlling all aspects of the prosthetic hand.[73] An alternative approach (cf. Kyberd[73]) is to feed back information about produced force or tactile information to the sensory system of the prosthetic user. Note that these aspects cannot be picked up visually. Broadly speaking, two approaches can be distinguished to close the perception-action loop. The first approach is to present feedback to a different modality on a different anatomical location on the body. This approach exploits the adaptive capacities of the sensory system to use alternative feedback signals for the benefits of prosthetic control[74] (cf. Winneger et al.[75]). An example of this is to attach a vibrotactile pad to the shoulder that produces a signal according to the force exerted by each fingertip (cf. Marasco et al.[76]). The second approach falls under the umbrella of neuroprosthetics, which aims at feeding back signals from the prosthetic hand directly to the sensory nerves.[77–79] Although most of these innovative techniques are still in their initial stages, these developments are promising. Note that several medical hurdles need to be cleared before these latter techniques can be applied to the average prosthesis wearer. Thus, in different research fields, several avenues must be explored to provide more detailed feedback about the state of the prosthesis to the user.

In summary, the control of reaching and grasping at the level of space requires direct feedback, which is currently lacking, in particular in myoelectric devices. However, several routes in the research field can be distinguished that aim at finding ways to deliver feedback about the prosthesis to the sensory system.

LEVEL OF ACTION

The highest level of control of movement regards the control of sequences of actions. This level of construction of movements is particularly important when manipulating objects. When picking up an object for manipulation, the goal of the manipulation determines how the object needs to be picked up. That is, the grip pattern with which the object is picked up should anticipate the goal of the task.[80,81] In sound grasping, it is shown that participants prefer an awkward initial posture of the arm and hand to have a comfortable posture at the end of the action, the so-called end-state comfort effect. For example, when picking up a glass that is standing upside down on a tray, the glass will be picked up with the thumb down (i.e., uncomfortable posture) to end up in a posture with the thumb up (i.e., comfortable posture) to put the glass somewhere. In principle, this preplanning of sequential actions should be facilitated for prosthesis users. This may suggest that when training pattern recognition–based classifiers, the prosthetic user should be encouraged to explore these awkward postures to be able to detect the appropriate grip type from the muscle activation patterns (cf. Fougner et al.[45]). Note that an alternative strategy can be to offload part of the control to the myoelectric hand itself, which is done in the Southampton Hand.[23]

A requirement for object manipulation is that prosthetic users can change between different grip types in a smooth and swift manner. The modern myoelectric prostheses allow for more grip types, and their multiarticulated digits improve the confidence that users have when holding an object (cf. Van der Niet et al.[27]). However, the transition between grip types of current myoelectric prostheses is slow and requires high attentional demands. Future improvements in prostheses should make the change between grip patterns easier and faster. Some of the suggestions in this article might offer some leads as to how this might be done.

LIMITATIONS

Finally, some limitations of the views presented previously are considered. It is important to take our starting point into consideration, that is, that a prosthesis changes the action possibilities of a user and that controlling a prosthesis dexterously requires that the prosthetic device can be easily integrated in the sensory-motor system. Prosthesis requirements were derived starting from the neuromotor processes involved in controlling the prosthesis. This is different from a user-centered approach (cf. Peerdeman et al.[18]) to define requirements of a prosthesis. We believe that these two approaches are complementary; that is, the functions a prosthesis should be able to perform can be defined from a user-centered perspective. The current article aimed to provide some ways in which prostheses and training programs should develop to make sure that users actually have easy access to all the functions of a prosthesis.

In this article, we limited ourselves to discuss prosthesis use by people who acquired an amputation. We believe that, in principle, most of the motor control processes with an acquired amputation are rather similar to the motor control processes with a congenital limb deficiency. Of course, it may be that the brain develops differently in the situation of a congenital limb deficiency compared with an acquired amputation (cf. Di Pino et al.[77]), but we are not aware of any papers showing the effect on motor control processes following this difference. Moreover, we restricted ourselves to discussing prostheses for a below-elbow deficit. We believe that the processes we discuss can also be applied to arm prostheses for more proximal amputations. In this respect, it should be mentioned that some people who have an above-elbow amputation use a hybrid prosthesis, where the elbow is controlled with body power, and the hand, with myosignals (cf. Bouwsema et al.[62]). When more joints are missing, more degrees of freedom need to be controlled, and it is often hard to find the appropriate anatomical locations to derive sufficient myosignals to control all the required degrees of freedom. However, the underlying processes should be the same. Interesting in this respect is the development of the Targeted Muscle Reinnervation surgical technique, in which residual arm nerves are transferred to alternative muscle sites that are not functional after the loss of the limb.[82–84] The muscle activity of these reinnervated muscles can be picked up from the skin with conventional electrodes, making these muscles function as amplifiers of the nervous system. The application of this technique is still in development, but the available results look promising.[84] This technique is fully in line with using the motor control processes to handle a prosthesis because the technique exploits the natural control of the missing limbs. For instance, when combining this technique with pattern recognition, the detected myosignals come close to representing the natural muscle synergies that produce hand movement.

CONCLUSIONS

In this article, the use of prosthetic devices is addressed from a motor control perspective. It was shown that current prostheses have some properties that are not optimal for their integration with the neuromotor system. However, several new technological developments are emerging that may lead to prostheses that are better aligned to what is required from a sensory-motor perspective. This enhances the possibility that future prostheses will be easier to use and increase the functionality of the person with a missing limb. Improving prosthetic training programs in line with problems of integrating the prosthesis in the neuromotor processes will further improve prosthetic functionality.

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