ABSTRACT: The role of muscle afferents is discussed in terms of their contribution to kinesthesia, the senses of position and movement of the limbs. It is argued that muscle spindles are not well suited as position sensors, on several grounds. Yet we know from muscle vibration experiments that they do contribute to kinesthesia. A number of recent experiments have shown that positional information is of particular significance to the central nervous system. In other experiments it has been demonstrated that a disturbance to kinesthesia follows fatigue from exercise. Fatigue of elbow flexor muscles led subjects to make significant positional errors in a forearm matching task. The size of the errors correlated with the fall in force from fatigue. These data suggest that we derive a positional cue from the effort required to hold a limb against the force of gravity. A challenge for the future will be to reveal how the centrally derived sense of effort and peripherally derived afferent information interact to give us our kinesthetic sense.

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WHAT IS THE ROLE OF MUSCLE RECEPTORS IN PROPRIOCEPTION?

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The topic of muscle receptors and proprioception is an old one that has been reviewed many times. Here I have chosen to begin with the Sherringtonian definition of what is a proprioceptor: "In muscular receptivity, we see the body itself acting as a stimulus to its own receptors—the proprioceptors."[30] Strictly speaking, there are many different kinds of receptors concerned with monitoring the body's actions. However, convention has restricted usage to four senses, the kinesthetic sense (i.e., the sense of position and movement), sense of tension, sense of balance, and sense of effort or of heaviness. Although the sense of effort is thought to be centrally generated and in its simplest form does not require any feedback from peripheral receptors, it is traditionally included in discussions of proprioceptors. There are circumstances in which the sense of effort and the peripherally derived sense of force are not easily distinguishable.

In this brief review, attention is focused on the kinesthetic sense and, in particular, on the sense of static limb position. I will argue that the class of muscle receptors to which this sense is currently assigned, the muscle spindles, in simplest terms, is not well suited to signaling positional information and, in the light of new experimental observations, the older idea of signals of central origin contributing to this sense should be reconsidered.

Although there is no doubt that muscle receptors, including muscle spindles and tendon organs, are involved in consciously perceived sensations, an important additional role is to provide peripheral feedback for unconscious, automatic adjustments during posture and locomotion. The importance of such a role is exemplified by their contribution to the stretch reflex. Muscle afferents provide feedback in response to centrally generated motor patterns, especially when unexpected loads or obstacles are encountered, to trigger the appropriate adjustments. This aspect of the function of muscle receptors is not discussed in detail here and the reader is referred to a recent review of the subject.[17]

KINESTHESIA

Over the years many different views have been put forward on this subject. The dominant view in the 19th century was that our kinesthetic sense is a consequence of the effort we make to move and arises within the central nervous system, providing us with a "sensation of innervation."[36] Sherrington did not share that view and favored the idea of a peripherally derived kinesthetic signal.[30,31] Subsequently, during

much of the 20th century, it was believed that kinesthesia was dependent on peripheral afferent signals, but they were thought to be largely of nonmuscular origin, arising in the joints.[33] It was the experiments of Goodwin et al.[12] that provided the first direct evidence that signals from muscle spindles generated sensations of limb displacement and movement.

The present-day view is that muscle spindles are responsible for the sense of position and movement, tendon organs provide the sense of tension, and the vestibular system the sense of balance, and that the sense of effort is generated within the central nervous system (CNS), as reviewed by Gandevia.[7]

However, considering specifically the sense of position, muscle spindles appear to have a number of drawbacks as position sensors. The most important of these is that spindles are under fusimotor control. Activity can be generated by stimuli arising from within the receptor, as a result of intrafusal contractions, or from without, as a result of muscle stretch. In terms of kinesthesia, this means that spindles provide a potentially ambiguous signal. In the simplest view, the positional signal provided by muscle spindles is thought to be generated by the passive receptor, that is, in the absence of fusimotor activity. As the muscle is stretched, there is an approximately monotonic increase in spindle firing rate with length. It is assumed that this signal is interpreted centrally in terms of limb position. Any impulse activity arising from intrafusal contraction is thought to be subtracted out.[21,23]

A minor point here is that, compared with other somatic senses, the CNS will have to use a different code to derive length information from spindles. It will be required to interpret an increase in firing rate as an increase in muscle length. Compare this with vision, hearing, and cutaneous mechanoreception, where an increase in firing rate is interpreted as an increase in stimulus strength.

Returning to the problem of the potentially ambiguous kinesthetic signal coming from spindles under fusimotor control, a historical perspective is again helpful. Two important sets of experiments for theories of feedback control of muscle are the work of Sperry[34] and of Von Holst and Mittelstaedt,[37] who proposed the term "efference copy," where the CNS compares the efferent outflow with the expected afferent feedback, the reafference. Under circumstances where the motor act proceeds as planned, the efference and reafference are subtracted from each other to achieve the null point. Any additional afferent feedback imposed by the external environment, "exafference," would be reported to sensory centers. Sperry introduced the term "corollary discharge" where the motor output is fed back directly to central sensory areas to produce a perceived sensation in its own right. For a more detailed discussion of these views, see Donaldson.[5]

The important idea put forward by Von Holst and Mittelstaedt was that the efference copy was designed to match precisely the reafference signal. In this way, afferent activity arising from the motor act itself could be accounted for. McCloskey[21] proposed that this kind of arrangement could apply to the fusimotor system as a means of deriving a meaningful kinesthetic signal from spindles. Any fusimotor-evoked activity would be subtracted from the total spindle signal, effectively leaving only the passive component of the response to be registered as a sensation. It is not clear how such a system would work in practice, given the variable relationship between motor output and reafferent signal. One fusimotor impulse may lead to the production of one afferent impulse, or a burst of impulses, or, at times, no activity at all.

It is necessary to postulate such a subtraction process since, as we all know, when we contract our muscles isometrically, the contraction is not accompanied by any sensation of displacement or movement. Yet it is known that when muscles contract, fusimotor neurons are coactivated together with skeletomotor fibers, leading to a large increase in spindle discharge.[35] So, presumably, if muscle length does not change, there is no exafferent signal and consequently no kinesthetic sensation. Such an end could be achieved by means of an efference copy (Fig. 1).

There is one reported observation in the literature that suggests fusimotor-evoked spindle impulses can produce conscious sensations. Human subjects underwent total body paralysis by infusion of a neuromuscular blocking agent. At one stage during development of the paralysis, subjects were asked to try to plantarflex their foot. Although no movement ensued, subjects reported a sensation of the foot rotating in the opposite direction, that of dorsiflexion.[10] Perhaps in the absence of confirmation by an exafferent signal that muscle shortening had occurred, the movement sensation evoked centrally by the corollary discharge led the subject to believe that their foot was moving in the opposite direction. The interpretation preferred by the investigators was that while all extrafusal fibers were blocked by the paralyzing agent, by virtue of their higher blocking threshold, some fusimotor neuromuscular junctions were still functioning.[40] As a result of the attempted contraction there was coactivation of fusimotor neu-
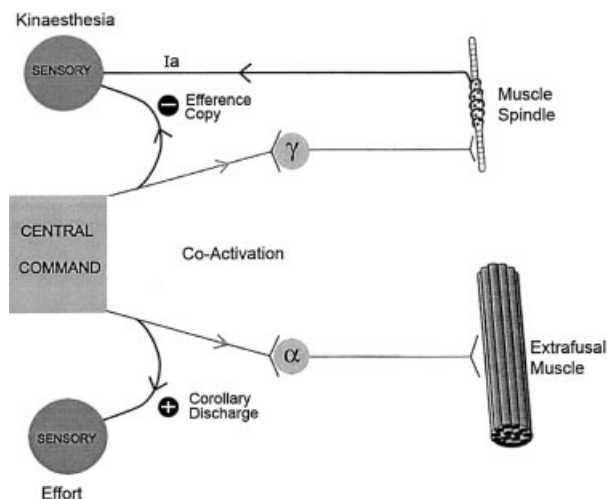
FIGURE 1. Diagrammatic representation of postulated central feedback processes accompanying motor output. Motor command signals are directed to the spinal motor neurons (α) to initiate muscle contraction. The command signal is fed back as a corollary discharge to sensory areas to generate a sense of effort. Accompanying the command to spinal motor neurons is a signal to fusimotor neurons (γ) as a result of coactivation. A copy of the signal to fusimotor neurons, the efference copy, is fed back to sensory area where this is subtracted from the total signal fed back by muscle spindles. The total signal comprises activity as a result of muscle length changes (exafference) plus activity from fusimotor activation (reafference). Redrawn, in part, from McCloskey et al.[23]

rons, leading to an increase in spindle discharge, which was interpreted by the subject as the muscle lengthening. In supplementary experiments, total muscle paralysis abolished the illusion, consistent with an interpretation based on incomplete paralysis.

One further difficulty with muscle spindles as position sensors that needs to be kept in mind is that the response of the passive spindle is dependent on the muscle's previous history of contraction and length changes. This relates to the fact that the intrafusal fibers exhibit thixotropy.[28] Again, reliability of the spindle signal for kinesthesia is questioned as it depends on what has been done to the muscle immediately beforehand.

Before discussing other ways in which limb position might be signaled, it is of interest to consider some recent observations relevant to a position sense.[2] Human subjects were asked to perform a series of repetitive movements from a visible starting position to a visible target without being able to see their hand. Over the 70 repetitions, hand location drifted away from the starting position, whereas movement direction and distance were remarkably preserved. The investigators concluded that propri-

oception continued to be a reliable source of kinesthetic information over time but that this was used differently by the CNS for determining limb position and for specifying movement trajectory. The significance of limb position for the CNS was further emphasized by recent mapping experiments of motor cortex in monkeys.[13] The data suggested some kind of postural coding in motor cortex. One possibility was that neurons were tuned to a particular posture, with the precision of tuning varying for different cortical sites. All of this suggests that limb position is a parameter of significance for the CNS and its derivation is different from that for the sense of movement.

THE SENSE OF EFFORT

We judge the muscle forces we generate and the heaviness of objects by means of a sense of effort.[21,23] The sense of effort is believed to arise centrally as a result of a corollary discharge (Fig. 1). Sperry[34] declared, in relation to eye muscle proprioception, that "a corollary discharge of motor patterns into the sensorium may play an important adjuster role in the visual perception of movement." The implication of this statement is that there is an interaction between the corollary discharge and afferent signals.[5] In a review of the contribution of proprioceptors to somatosensory mapping, Peter Matthews wrote ". . .the interest now is not in asking simply whether corollary discharges are involved in the genesis of human position sense, for it seems to me that they must be."[19]

In his recent comprehensive review, Donaldson[5] presented the various pieces of evidence in support of "outflow" and "inflow" mechanisms for the control of eye movements and gaze. He concludes that neither outflow mechanisms alone nor inflow mechanisms alone are able to adequately explain the various observations. One estimate is of 70:30 in favor of outflow[11]; another is 80:20 in favor of inflow.[18] Clearly, therefore, a major challenge for the future will be to establish the proportional contributions of the two systems and how they might cooperate in achieving adequate position and movement control.

A clue about how proprioceptive afferent feedback interacts with an output signal is provided by an experiment using muscle vibration.[32] A subject sitting in the dark is asked to track a moving light with his arm while arm muscles are being vibrated. The vibration-evoked illusion of muscle lengthening leads the subject to make tracking errors. Then the subject is told to move the arm rapidly to align it properly with the light. Although this makes no

sense to the subject, who believes that accurate alignment has already been achieved, he responds to the instruction and overcomes the vibration illusion to align his arm accurately. The observation suggests that there is more than one map of limb position in the brain and that motor acts make reference to a different map from that accessed by sensory input, one that is not the subject's first choice. The motor map remained unaffected by muscle vibration, whereas the sensory map was distorted by it. The illusions seen in subjects after whole-body paralysis[10] could be interpreted in terms of conflicting information reaching sensory and motor maps.

Evidence that the effort and position control systems can be accessed facultatively has been demonstrated for an arm-reaching task when there is a force perturbation during the reach.[16] Subjects were instructed to achieve a spatial goal in an arm-reaching task carried out under visual control. They showed terminal compensation to the force-induced displacements, suggesting feedback control. Feedforward control was also apparent from the smaller path deviations during repeated trials. There was some after-effect when the force perturbation was removed. When subjects were asked to maintain a constant effort in the face of the force perturbation, they exhibited large deviations from the target, indicating an absence of feedback compensation. They also showed no feed-forward compensation during repeated trials and no after-effects. All of this suggests two distinct control mechanisms, perhaps associated with distinct central reference frames.

In a number of reports in the literature, the force of gravity was altered experimentally, leading to disturbance of proprioception. In one example,[24] subjects were asked to match a perceived level of force by adjusting a variable force. Under control conditions matches were quite accurate, but when the task was repeated under microgravity the matching force was systematically overestimated.

The sense of effort is linked to the sense of fatigue. The term fatigue, as employed in common usage, suggests exhaustion. The more rigorous scientific meaning includes a collection of mechanisms, ultimately expressed as a decline in muscle force during repeated activation. There are peripheral mechanisms as well as mechanisms within the CNS that contribute to the decline in force.[8] During exercise, as muscle force declines, the CNS compensates by increasing activation of motoneurons, leading to a progressive increase in the perceived effort, until the point of exhaustion is reached.

An important question is where in the brain the sensation of effort is generated. Knowing the site of

origin might help in better understanding how this sense cooperates with motor output. We know from the technique of transcranial magnetic stimulation that the motor response from stimulation of the motor cortex is not accompanied by any sensation of effort.[6,10] Experiments on fatigue suggest that the changes during exercise occur somewhere upstream of the motor cortex, and there appears to be a failure of drive to the motor cortex.[9] All of this leads to the view that the effort signal is not simply derived from a copy of the output of the motor cortex, but arises somewhere upstream.[4,26] It will be a challenge for the future to define more precisely the central site of origin of the effort sensation and how this is linked to the output from the motor cortex.

ECCENTRIC EXERCISE

The author entered the debate about positional coding and the sense of effort from an unexpected direction. For a number of years we had been studying the changes in mechanical properties of skeletal muscle after a period of eccentric exercise, where the contracting muscle is lengthened. We use our muscles eccentrically to control movements such as during downhill walking or in landing from a jump. Persons unaccustomed to eccentric exercise exhibited a large drop in force in the exercised muscles immediately after exercise. In addition, they experienced stiffness and soreness in their muscles the day after exercise as a result of muscle damage. This area of study was reviewed by Proske and Morgan.[27]

It is a common experience that, after a period of intense exercise, we feel unsteady on our legs and have difficulty in carrying out skilled movements. This is particularly so after eccentric exercise and evidence has been put forward for a disturbance to proprioception from such exercise.[1,29] Since the delayed muscle stiffness and soreness from eccentric exercise is known to be the result of localized damage to muscle fibers,[27] it raised the possibility of an effect on muscle sense organs as well, and that this led to the disturbed proprioception.

These facts led the author and his colleagues to embark on a study of the effects of eccentric exercise on muscle proprioception. We first studied the sense of tension. The present-day view is that we have a peripherally derived sense of tension, probably arising from signals in tendon organs.[22] In addition, we have a sense of effort or of heaviness that is believed to be generated within the CNS (Fig. 1). That there is a peripheral component to force sensation is demonstrated by the errors produced in a force match-

ing task where the contracting muscles of one limb are vibrated.[3,22]

In our experiment, subjects were asked to generate an isometric force in elbow flexors of one arm and to match this with their other arm. Subjects could perform such a task quite accurately. However, after one arm was exercised eccentrically, subjects made large and consistent matching errors. The errors were very much smaller when expressed in terms of the lower force generated by the exercised arm. It suggested that subjects were using their sense of effort to match forces, not a peripherally derived sense of tension. A peripheral signal would have indicated the true level of tension and, therefore, would not have led to matching errors.[4,39]

To further verify this point, a series of animal experiments was carried out, measuring the response properties of tendon organs before and after a series of eccentric contractions.[14] It was found that the contractions led to a 40% drop in muscle force, accompanied by other indicators of muscle damage, yet the responses of tendon organs to muscle stretch and contraction remained unchanged. It was concluded that force matching errors after eccentric exercise were not the result of a disturbance of function in tendon organs. The explanation that best fitted the facts was that subjects were matching forces by matching the amount of effort required to achieve a given level of force. Do tendon organs play a role at all in the sense of force? The vibration experiments suggest that they do. Our current working hypothesis is that tendon organs provide a calibrating signal for the sense of effort.

We next examined whether eccentric exercise disturbs kinesthesia, as had been suggested by previous reports.[1,29] An experimental arrangement was used which was similar to that for force matching. Blindfolded subjects had one forearm placed at a particular elbow angle and were asked to match the angle with their other forearm. Again, subjects were quite accurate in such a task and, provided they made the match without their arms being supported, could achieve an accuracy of ±2°–3° of elbow angle. Then one arm was exercised eccentrically, leading to an average fall in force of 46%. Subjects were asked to match elbow angles at various times after the exercise, up to 1 week later (Fig. 2). Subjects made significant position matching errors, which were greatest immediately after the exercise. The size of the matching errors correlated with the drop in force. Some, if not significant, errors persisted for 4 days.[38] The pattern of errors suggested that subjects were using the sense of effort to locate the position of their arm. To hold the arm at a set angle against
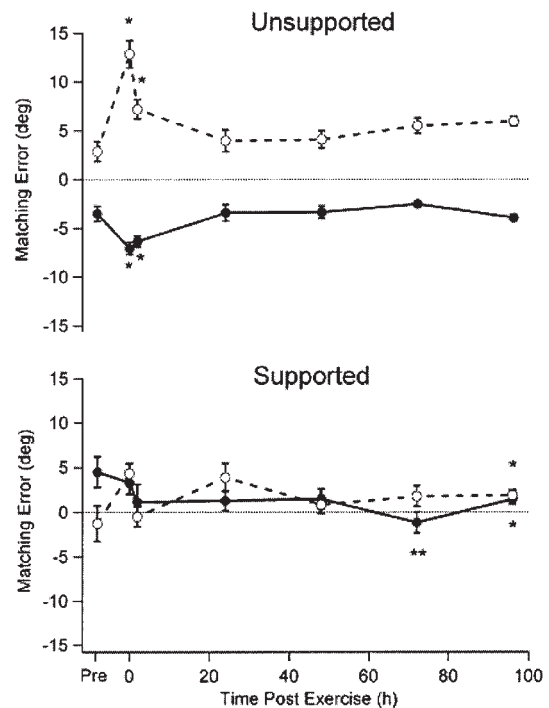

FIGURE 2. Position matching errors after eccentric exercise. Forearm position matching errors for one subject, pooled from measurements at three different angles (30°, 60°, 90°). Forearm angles were expressed in degrees above the horizontal, which was assigned 0°. When matching errors were in the direction of elbow flexion, they were given a positive value, and in the direction of extension a negative value. Dashed line and open symbols: reference arm unexercised; continuous line and filled symbols: reference arm exercised. Zero error is indicated by the dotted line. Errors were measured before a period of eccentric exercise of elbow flexor muscle (Pre), immediately afterwards (0 h), and at 24, 48, 72, and 96 h. Values are means (± SEM) from combined data from five trials for each of the three angles. Asterisks indicate points significantly different from control. **(Top)** After the reference arm had been placed at a particular angle by the investigator, the subject was asked to maintain that angle (unsupported) while matching it with their other arm. **(Bottom)** The reference position was maintained by a support (supported) and the subject was asked to fully relax their reference arm during the matching procedure. Redrawn from Walsh et al.[38]

the force of gravity, unsupported, requires a certain amount of effort. The perceived effort increases significantly if arm muscles are damaged and fatigued from eccentric exercise. If subjects match efforts to align their arms they will place the fatigued arm more nearly vertically where less force is required to support it. That, in turn, leads to position matching errors.[38] If the effort cue is removed from the reference arm by supporting it, matching errors become erratic and are no longer correlated with the decline in force (Fig. 2).

Again, we considered the possibility that at least some of the matching errors were the result of dam-

age to muscle receptors. Damage in muscle spindles was more likely than in tendon organs, since spindles have intrafusal fibers and it seemed plausible that the eccentric contractions were able to damage both extrafusal and intrafusal fibers. We therefore performed a series of animal experiments in which we looked at the responses of identified muscle spindles before and after a series of eccentric contractions.[15] As for tendon organs, the responses of spindles to stretch and to intrafusal contractions did not change significantly after the eccentric contractions (Fig. 3), even though the muscle showed evidence of damage, including a 46% drop in isometric force.

We concluded that the observed disturbance to proprioception after eccentric exercise is not the result of dysfunction of muscle sense organs. Rather, our observations led us to conclude that, in the
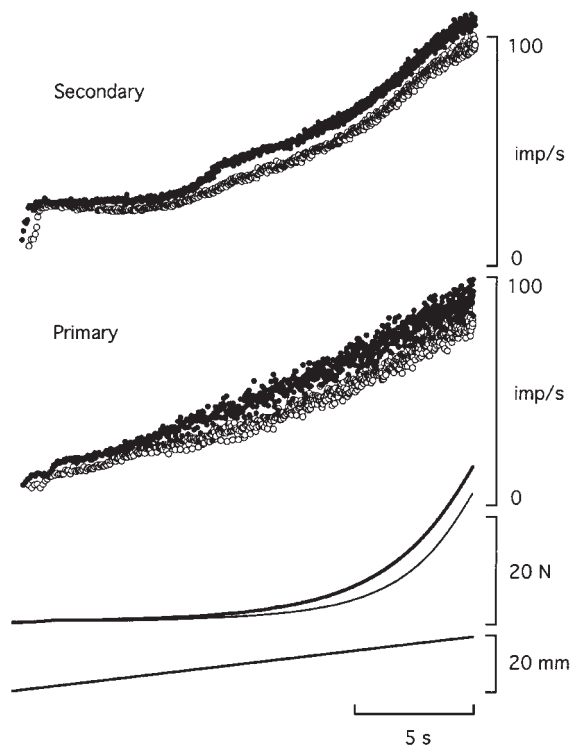

FIGURE 3. Responses of muscle spindles before and after eccentric exercise. Responses of single identified afferents of a secondary spindle ending **(top)** and a single primary ending **(middle)**, before (open circles) and after (filled circles) 50 eccentric contractions of the medial gastrocnemius muscle of the anesthetized cat. Afferent discharges are shown as instantaneous frequency displays. Responses were recorded to a slow stretch at 1 mm.s^{-1} covering the full physiological range (20 mm). The muscle length change during the stretch is also shown **(bottom)**, with the accompanying passive tension changes immediately above. Thin line curve: recorded before eccentric contractions; thick line curve: recorded after the contractions. Redrawn from Gregory et al.[15]

position holding task tested, the sense of effort plays a major role. We proposed that, during active placement of our limbs, we use, as a positional cue, the sense of effort required to maintain limb position against the force of gravity. Taking the forearm position matching task as an example, to account for the direction of the errors after exercise, if elbow flexors in the reference arm are fatigued, the indicator arm adopts a more extended position to match it. This is because the larger effort signal from the fatigued reference arm leads the indicator to move to a more horizontal position, where more effort is required to maintain it.[38]

For advocates of muscle spindles as the primary position sensors, there is an alternative explanation: as a result of fatigue, there is more coactivation of spindles to maintain position of the arm and this larger spindle signal leads the indicator arm to adopt a more extended position where elbow flexors are more stretched, increasing the spindle signal. The difficulty with this, according to the McCloskey[21] proposal, is that any change in the coactivated afferent signal represents a reafference and it should be subtracted out centrally by efference copy (Fig. 1).

CONCLUSIONS

The view of kinesthesia that I have taken in this review is an intentionally oversimplified one. I have assumed that muscle spindles are accorded the principal role as signalers of position sense. However, it has been repeatedly shown that, for movements at many joints, both skin and joint receptors play a contributory role. I have treated the problem of subtraction of fusimotor activity in its simplest terms, even though central processing is likely to be much more complex, in view of the multimodal nature of the input. By simplifying the account in this way, I had hoped that the way forward for future experiments might be revealed more clearly. Studies of the effects of fatigue from exercise on proprioception seem to be one such useful direction.

Interpretations based on the effects of muscle fatigue and damage suggest that, for both the sense of tension and the sense of limb position, subjects make use of a centrally derived sense of effort. By this, it is not intended to imply that muscle receptors are not involved. Obviously, both spindles and tendon organs contribute to proprioception, based on the illusions evoked by muscle vibration. It can be argued, however, that spindles are not well suited to signal static limb position when this is achieved by placement of the passive limb.[25] Position sense becomes much more precise if active placement is

used. In interpreting such observations, it is well worth reflecting on what is known from studies of eye-muscle proprioception, and to consider the possibility that both output-derived and input-derived signals contribute.[5] It will be a challenge for the future to determine precisely how such a system might work.

All of our movements are carried out in a gravitational field and overcoming gravitational forces provides us with spatial cues. It comes as no surprise that, in the absence of visual control, astronauts in outer space encounter difficulties in the execution of motor tasks.[20,41] The same is likely to be true for scuba divers. All of this means that we should reevaluate the role of peripheral feedback in position sense. An important question for the future is whether effort plays a role in position sense where placement of the limb is independent of gravity, as with abduction–adduction movements about the elbow joint in the horizontal plane. Conceivably, some effort is involved in such tasks, but this would not be expected to change systematically with elbow angle unless it was to maintain forearm position in the face of changing passive tension in stretched antagonists. If so, the effort signal would have to access a different frame of reference from that used to locate the forearms with the hands-in-front posture. These are matters for future experiments.

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