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REVIEW

The neural basis of the senses of effort, force and heaviness

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Abstract
Effort, force and heaviness are related terms, having in common that they are all sensations associated with the generation of voluntary muscle contractions. Traditionally they have been thought to originate in the brain, as a result of copies of motor commands relayed to sensory areas. A stumbling block for the central hypothesis has been the lack of proportionality between the fall in muscle force from fatigue or paralysis and the increase in sensation generated while trying to achieve the required force. In recent times growing evidence has accumulated supporting a role for peripheral sensory receptors, in particular the muscle spindles, as contributing to these sensations. The review discusses the evidence for participation of sensory receptors and what this means for proprioception. In particular, it is not straightforward to envisage how muscle spindles might provide a reliable force signal in a contracting muscle, with or without support from the fusimotor system. An important additional consideration is the method of measurement. It has emerged that there is evidence of a task-dependency in the composition of the afferent signals contributing to the sense of force. The evidence suggests that the signal used in a two-arm force matching task is not the same as in a one-arm task. It will be important, in the future, to try and obtain more direct evidence about the afferent origins of the senses of effort, force and heaviness, how they might change from one task to another and what implications this has for motor control.

Keywords Force sense · Proprioception · Muscle spindle · Tendon organ · Motor command · Efference copy · Vibration

Introduction

The senses of effort, force and heaviness are traditionally part of a group of senses, the proprioceptive senses, which include the senses of position and movement of the body and the sense of balance. The proprioceptive senses are sensations that arise from the actions of our own bodies, yet they are also sensations which we mostly do not attend to, unless we are trying to learn a new, unfamiliar task or we have actions imposed on us unexpectedly by external sources. In discussing the sensory origins of the senses of effort, force and heaviness we have employed the term, “sense” rather than “perception”. Here we are following common usage and we include in the meaning of the term both the afferent processes initiated by muscle contraction and their central transformation into a perception.

In all discussions of proprioception, an important consideration is always the method of measurement. Traditionally, position sense (Proske and Gandevia 2018) has been measured in terms of the accuracy in reproducing or matching a particular joint angle. However, evidence suggests that information available to the central nervous system must be considerably more precise than what is consciously perceived at a particular joint (Van Beers et al. 1998). It has been proposed that proprioception is normally used to automatically control movements, not to create conscious percepts of limb orientation (Darling et al. 2018). Such considerations raise the spectre of a sensory system which operates at a level of precision of which we remain unaware and which our simple experiments do not necessarily reveal. This has to be kept in mind when assessing the evidence thought to underlie the operations of the senses of force and heaviness.

The terms, “effort”, “force” and “heaviness” are related in their meaning and are no more than descriptions of the subjective sensations we experience. Traditionally, the term ‘effort’ has been used for a sense that is believed to take its

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origin entirely from within the central nervous system. The sense of muscle force or tension has been considered to be generated by central as well as by peripheral influences and it may involve the signals of a muscle's force sensors, the tendon organs. The sense of heaviness relates to the weight of objects and here there is a hint of a peripheral afferent contribution to the sense. It is a common experience when we are asked to compare the heaviness of two objects placed in our hands that in making our judgement, we move the objects up and down. Subjects are less accurate in heaviness discrimination tasks if the movements are not allowed (McCloskey et al. 1974). Such behaviour is suggestive of a movement sensitive, afferent contribution to this sense. Here we have tended to use the three terms, according to their common usage, being mindful of the important question of whether they arise centrally or include a peripheral contribution.

The subject of the senses of effort, force and heaviness has been reviewed before. In 2012 we provided a comprehensive account that covered most aspects of the subject (Proske and Gandevia 2012, p 1671). However, since then a number of additional reports have been published which throw new light on aspects of the subject. We therefore wanted to revisit the topic and provide a brief update. We have chosen to restrict the discussion to one of the main issues, the afferent origins of these senses, an area of immediate interest to the wider readership. The review is therefore relatively brief and focussed. As a consequence, subject matter somewhat peripheral to the topic has not been covered, such as the relationship between perception and action and the dependence of motor commands on perceived object properties, such as the size–weight illusion. In our assessment of the material, we have come to the conclusion that significant gaps continue to exist in our understanding of the subject. We have therefore chosen not to adopt a dogmatic approach, but preferred to point to future directions for research.

Historical perspective

The history of the evolution of our understanding of this subject is fascinating and a brief summary is warranted. The concept of a muscular sense is attributed to Bell (1826). At the time the prevailing view held by German physiologists was that the muscle sense did not arise in the muscles themselves, but in the brain. It was referred to as a "sensation of innervation" (Müller 1837; Helmholtz 1867). The idea was that whenever we willed a movement, this gave rise to central sensations of muscular activity and movement. The "father of modern neuroscience", Charles Sherrington (1900) did not support these ideas. He made the simple point that since we were aware of the position of our limbs, even when they lay passive, unmoving, such a sensation could not arise entirely within the brain. Sherrington believed that there were peripheral proprioceptors responsible for muscular sensations. At the time, the only one who considered the possibility that both points of view might be correct, with sensations being able to arise both centrally and within the periphery was Bastian (1888). His propositions form the basis of present-day ideas about the generation of the senses of effort, force and heaviness.

We are all familiar with the sense of effort. When we carry heavy objects, like a full suitcase, over time, as our muscles fatigue, the suitcase appears to become heavier. To prevent the suitcase from dragging along the ground, we automatically increase the central command to our arm muscles, raising the perceived effort and leading to the sensation that the suitcase is getting heavier. A related phenomenon is the patient recovering from surgery who still retains some circulating muscle relaxant given during the surgery. They complain of the heaviness of their limbs when they try to lift them. The muscle relaxant has weakened muscles and a larger motor command is required to overcome the paralysis, leading to an increase in the sense of effort. These sorts of considerations have led to the view that the sense of effort is generated entirely centrally, within the brain.

McCloskey et al. (1974) claimed that if subjects were appropriately instructed, they had the ability to facultatively select between a sense of effort generated centrally and a sense of force, presumably arising in sensory receptors in the periphery. In a two-arm force matching task, subjects were asked either to match the perceived effort, or to generate a matching tension. Disturbance of muscle force output by vibration could be largely compensated for with the tension instruction, but not with the effort instruction. Roland and Ladegaard-Pedersen (1977) shared that view and proposed that the peripheral receptors involved in the tension sensation were the tendon organs. While that may be so, it is difficult to see how tendon organs could participate in a sense of effort. If perceived effort rises during fatigue or paralysis this cannot involve tendon organs whose signals will faithfully follow the declining force.

Muscle vibration has proved to be a powerful means of disturbing proprioceptive signals coming from muscle. McCloskey et al. (1974) reported that in a force-matching task vibration of biceps of one arm led subjects to match the force generated by the vibrated arm with smaller forces in the other arm. When the vibration experiment was repeated on quadriceps, the opposite result was obtained, the non-vibrated indicator generating more force than the vibrated reference (Cafarelli and Kostka 1981). Our own observations on elbow flexors have confirmed this result. For a group of eight subjects instructed to match efforts in their arms, during vibration of the reference arm which was generating a 20% maximum voluntary contraction (MVC), the indicator force overshot the reference value by 20%. However when subjects were instructed to match forces in their muscles, not efforts, the errors were no longer significant (W Garvey, T J Allen and U Proske, unpublished observations). Our interpretation for the effort instruction was that vibration engaged tendon organs in the contracting muscle. This led to inhibition of segmental motoneurones and in order to overcome the inhibition, the effort required by the reference arm to reach the target force was increased. The same effort applied to the unvibrated muscle therefore led to generation of higher forces. For the force instruction we assumed that despite the vibration evoked disturbance, subjects were able to access a tendon organ signal that gave an accurate indication of active tension in the muscle and which could therefore be accurately matched.

The reason for the different outcomes in the above experiments is most likely attributable to the complex nature of the vibratory stimulus. Vibration will stimulate the 1a fibres of muscle spindles (Roll et al. 1989), in some subjects generating a tonic vibration reflex, the vibration equivalent of the stretch reflex (Hagbarth and Eklund 1966). This was the explanation used by McCloskey et al. (1974). They proposed that in the reference arm the vibration generated some force through the tonic vibration reflex, which meant that the subject required less effort in that arm to achieve the target force. When subjects were matching efforts, this led to an undershoot in the matching force generated by the non-vibrated arm. So the differing observations by Cafarelli and Kostka and ourselves, on the one hand and McCloskey et al on the other, could be reconciled, depending on whether or not the vibration had generated a reflex contraction. Given that not all subjects show a reflex response to vibration, here the lesson is that in a force matching task where one arm is vibrated, evidence should always be sought for the presence of a reflex response using force measurements and recordings of electromyographic (EMG) activity.

Vibration will also generate sensations of movement of the muscle (Goodwin et al. 1972) and it can alter the muscle's thixotropic state (Gregory et al. 1988). In a contracting muscle, the vibration will stimulate afferents of tendon organs (Fallon and Macefield 2007) leading to segmental reflex inhibition. Finally, if vibration is maintained for longer periods, 10–20 min, it can lead to a rise in threshold to electrical stimulation of large muscle afferents (Coppin et al. 1970; Heckman et al.1984) and their desensitisation to mechanical stimulation (Pope and De Freitas 2015). So in interpreting the effects of vibration it is always necessary to take these various influences into account.

Two reports, both published in 1950 have had a lasting influence on our thinking about the senses of force, effort and heaviness. Sperry (1950) introduced the term "corollary discharge", meaning a copy of the motor discharge sent to sensory areas of the brain (Fig. 1). The proposal was that sensory areas were under the influence, both of copies of the motor discharge, as well as incoming sensory signals generated in the body periphery as a consequence of the motor acts. In the same year, von Holst and Mittelstaedt (1950) added an extra element by introducing the concept of "reafference". This was the afferent activity generated by the body's own actions and which was anticipated, based on past experience or the operation of a forward model (Bays and Wolpert 2007). There are reasons to believe that reafferent signals do not always reach consciousness (Proske and Gandevia 2012). So in everyday activities our sensory areas receive information generated by external influences, the exafferent signals, as well as signals related to movement of the body, the reafference (Fig. 1). The total afferent signal reaching sensory areas of the brain will typically have both exafferent and reafferent components. Thinking in these terms has benefited the development of our ideas about the generation of proprioceptive sensations.

Recently attempts have been made to study the operation of forward models under changing conditions like, for example, during fatigue from exercise. How is the central nervous system able to predict the outcome of a motor command in the face of fatigue? One suggestion is that in the fatiguing muscle the metabolic products of the exercise stimulate muscle afferents in the Group III and Group IV range and they act to on motor areas to adjust the efference copy signal so that fatigue-generated changes in muscle output are taken into account (Monjo et al. 2015).

While the concept of forward models has widespread appeal, it should be remembered that there is only limited supporting evidence for the operation of such a process. A recent study has thrown doubt on the need for forward models to provide accurate localisation information during hand movements (Darling et al. 2018). Subjects were tested for their ability to touch the tip of the index finger of the moving left hand with their right index finger. The test was done under three conditions: (1) with vision available, subjects moved their target finger themselves; (2) active movement of the target finger in the absence of vision and (3) passive movement of the target (moved by the experimenter) in the absence of vision. Subjects were similarly accurate in all three tasks. It was concluded that proprioceptors were able to provide accurate localisation information (perhaps calculated using a vector distribution of population responses of muscle afferents; Proske and Gandevia. 2012, p 1663) and it was not necessary to postulate estimates of arm kinematics derived from internal models to contribute to localisation accuracy beyond that provided by sensory signals.

While accepting this result for the kinaesthetic senses, it is difficult to see how such considerations can apply to the senses of force and heaviness. Both can be manipulated by altering muscle output with fatigue or paralysis, implicating a role for the motor cortex in the generation of these

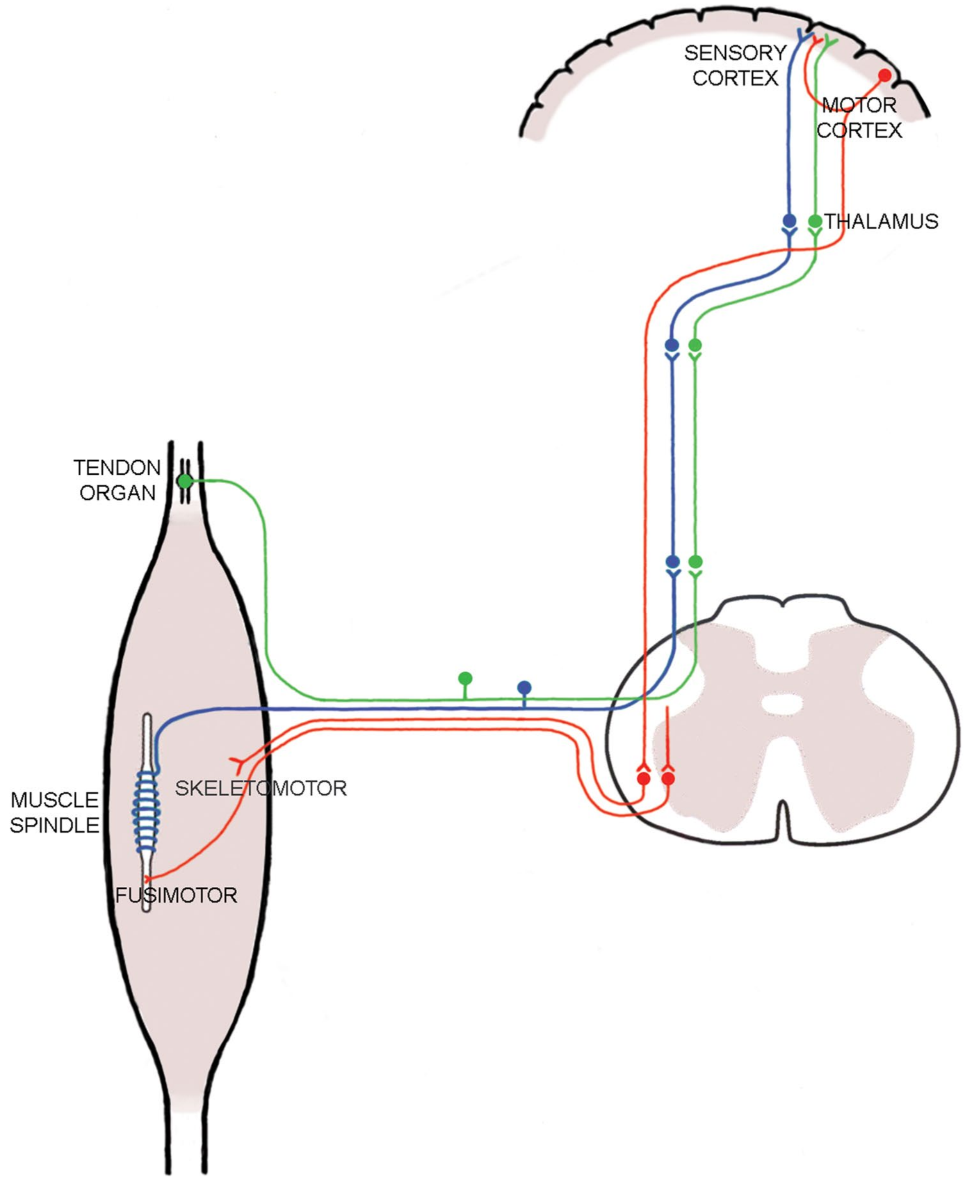


Fig. 1 Sketch diagram of postulated pathways taken by activity arising in sensory receptors and in motor cortex concerned with generation of the senses of effort, force and heaviness. Motor commands, generated in motor cortex, are transmitted by corticospinal neurones down the spinal cord where they synapse on spinal motoneurones. These send their impulses to contract muscles involved in exerting a force or lifting a load. Intermingled amongst the spinal motoneurones are the fusimotor neurones activated by pathways originating in the brainstem. These neurones selectively innervate the intrafusal fibres of muscle spindles to excite them during contractions. Collaterals of cortical motoneurones project to sensory cortex where they are involved in the generation of the sense of effort. Sensory receptors stimulated during muscle contraction, the muscle spindles and tendon organs, send their impulses along afferent fibres that project to the spinal cord where they synapse to continue as spinocerebellar tract neurones, making further synapses in the brainstem and thalamus before terminating in sensory cortex. Sensations of force and heaviness are generated by processes in sensory cortex as a result of the combined influences of impulse activity arising in muscle receptors and in collaterals coming from motor cortex

sensations. This does not, of course, exclude the possibility an additional contributory influence from peripheral receptors.

Recent developments

Until recently, prevailing views about the origin of the senses of effort, force and heaviness were dominated by the belief that they were generated entirely within the brain. A model based purely on central influences seemed to provide the most satisfactory explanation for the well-known disturbances of these senses produced by muscle fatigue (McCloskey et al. 1974; Jones and Hunter 1983; Carson et al. 2002; Weerakkody et al. 2003) and muscle paralysis (Gandevia and McCloskey 1977a, b; Gandevia et al. 1980).

In 2011 a report by Luu et al. revisited the question of a contribution by peripheral afferents to the senses of force and heaviness. The outlook adopted by these authors was strongly influenced by the von Holst concept of reafference and exafference. They pointed out that the reafference generated by peripheral receptors could equally well be considered to be generated centrally since it represented the sensory consequences of motor commands. They saw such a view as blurring the distinction between afferent and efferent and argued that the two should be considered together as part of a single process. Luu et al. opened their argument about central and peripheral contributions to the senses of force and heaviness by pointing out that during muscle fatigue, while the perception of force and heaviness increased, the perceived increase fell well short of that anticipated if a purely central mechanism were operating.

In a two-arm heaviness matching experiment using thumb flexor muscles, Luu et al. (2011) showed that if a subject was asked to generate an MVC with one thumb, continuously, to the point of fatigue and then lift the reference weight, the matching weight chosen by the other, unfatigued thumb, was significantly less than before fatigue. This was exactly the opposite result to that predicted by a centrally generated sense. In a second experiment, thumb flexors on one side were fatigued in two subjects who had large sensory fibre neuropathies. These subjects had no muscle spindles or tendon organs to provide peripheral feedback during heaviness sensations, so they were obliged to rely on a purely centrally generated sense. In the event, for both subjects, reducing the strength of thumb flexors on one side by half with fatigue led to a doubling of the perceived reference weight supported by the unfatigued thumb. Such a result was expected if a purely central mechanism was operating and, by inference, it pointed to something different going on in normal subjects, since there the increase in matching force after fatigue falls well short of a doubling of its value. In addition, it showed that the peripheral afferents involved in the sense of heaviness were served by large-diameter fibres and not by fibres in the Group III and IV range, which remain functionally intact in deafferented subjects.

The deafferented subjects were unable to carry out the weight discrimination task in the absence of vision. It has been pointed out that they may well have been making their judgement based on vision of the onset, size and speed of the movement they generated during their lifting effort and that performance was not dependent on central command signals at all (Darling et al. 2018).

Luu et al. (2011) proposed that in normal subjects there was a substantial peripheral afferent component to the sense of heaviness, to the point that, if the fatigue was severe enough, lifted objects felt lighter rather than heavier, presumably because of the peripheral afferent desensitisation accompanying the fatigue. Evidence to support such an interpretation was provided by another experiment where the subject maintained a 40% MVC contraction to fatigue with one hand. Afterwards, the weight supported by the fatigued hand did not feel lighter unless during the fatiguing contraction the muscle was vibrated as well. Presumably the vibration had sped up the rate of desensitisation of the peripheral afferents during the contraction, leading to a reduced sensation of heaviness.

In a force-matching task, Luu et al. (2011) required subjects to generate an MVC with thumb flexors of one, the reference hand, and at regular intervals match the perceived force level with thumb flexors of their other, indicator hand. It was found that indicator force was always greater than reference force, although both declined steeply with time. Luu et al. made the point that had a purely central mechanism been operating, indicator force should not have declined but remained at maximum levels. If a purely peripheral signal was responsible, indicator force should have faithfully followed the declining reference level. Something in between was observed, suggesting both central and peripheral components to the force signal.

The experiments of Luu et al. (2011) provided one additional observation which pointed directly to the muscle spindles as receptors contributing to the sense of heaviness. Here, by infusing a neuromuscular blocker, one arm was paralysed to the point where no EMG activity could be detected in arm muscles during attempted contractions. Recovery from paralysis was monitored and when thumb flexor force had returned to 40% MVC subjects carried out a series of weight matches. Lighter weights were chosen by the unparalysed side to indicate the weight supported by the paralysed hand. Again, this was the opposite result to expectations if a signal of central origin had been involved. The interpretation of the result is based on the assumption that deep paralysis leads to block of both the extafusal and intrafusal motor terminals (Fig. 1). It is known that during recovery from neuromuscular blockade, the intrafusal motor terminals unblock more slowly than extrafusal terminals (Smith and Albuquerque 1967; Yamamoto et al. 1994). A situation can arise where many extrafusal terminals have recovered and contraction of these muscle fibres can unload any ongoing spindle discharges. At the same time, given that the subject is carrying out a voluntary contraction, since intrafusal motor terminals remain blocked, the spindles are unable to be excited through fusimotor co-activation (Vallbo 1971, 1974). As a consequence, the spindle signal coming from the partially paralysed muscle remains low, leading to a sensation of reduced heaviness. It was concluded that an important source of peripheral signal to the sense of heaviness was the activity of muscle spindles, proprioceptors traditionally associated with the senses of position and movement.

At the time of their presentation, these ideas were quite novel and, unsurprisingly, they were met with considerable scepticism by workers in the field. It prompted new experiments seeking confirmatory evidence. Here one consideration was that all of the reported experiments had been done on the thumb, with the thumb pressing down to lift a weight, a somewhat unnatural task. It was therefore important to know whether the results of Luu et al. (2011) applied as well to other muscles and in more natural tasks.

In a series of force-matching trials using elbow flexor muscles, Brooks et al. (2013) asked subjects to carry out a continuous, 100% MVC with their reference elbow flexors, and at regular intervals produce matching forces with their unfatigued indicator arm. For the example subject shown in Fig. 2 (top panel), reference force was overestimated, while both reference and indicator forces fell steeply, as had been observed by Luu et al. (2011) and which was contrary to expectations, if a purely central influence had been operating.

However, for the group of subjects, during the matches there was not always the steep fall in indicator force (Brooks et al., Fig. 3). The most likely reason was that, unlike for thumb flexors, in elbow flexors subjects found it difficult to regularly and reliably generate MVCs. At the elbow several groups of much larger muscles are involved, compared with the thumb. The metabolic demands by elbow muscles to maintain a maximum contraction are therefore likely to be greater as well. Finally, it is important for this kind of experiment that highly motivated subjects are chosen. Perhaps some subjects in this group lacked sufficient motivation.

When the target force in the reference arm was reduced to 35% MVC, subjects again overestimated force levels. The amount of overestimation could be reduced with 80 Hz vibration applied to biceps brachii of the reference arm during the ongoing contraction (Fig. 2, middle and bottom panels). Such a result could not be explained in terms of a central mechanism and it implied that the peripheral afferent signal engaged by the vibration most probably came from muscle spindles since vibration can lead to their desensitisation (Pope and De Freitas 2015). It remains uncertain whether tendon organs show a similar desensitisation during vibration.

In a related series of experiments on the sense of heaviness, Brooks et al. (2013) obtained further evidence for the operation of a peripheral signal. A significant fall in perceived heaviness was observed with fatigue generated by a continuously maintained 100% MVC. There was no fall in heaviness sensation when force was reduced to 35% MVC, unless this was combined with vibration. Again, such results cannot be interpreted in any simple way in terms of a purely central mechanism and they implied a contribution to the sense of heaviness from peripheral receptors.

In a further search for evidence of a peripheral receptor contribution to the sense of force, Savage et al. (2015) adopted a rather different approach. Traditionally, in experiments on the sense of force, the sense is disturbed with fatigue, paralysis or vibration. Another means of altering the force output of a muscle is to take advantage

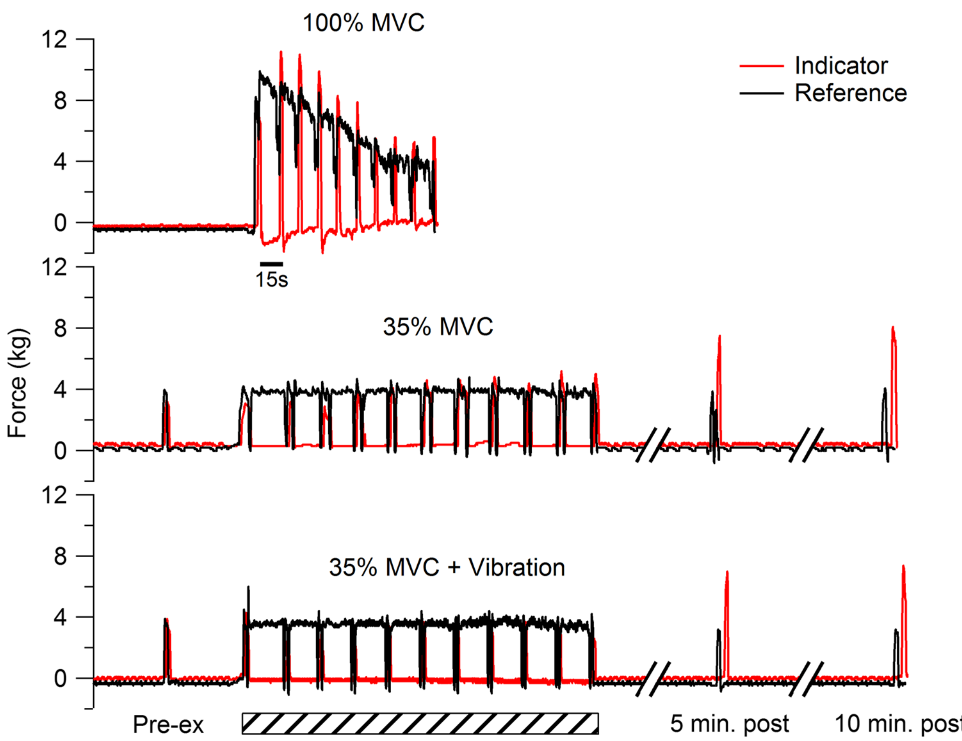


Fig. 2 Isometric force-matching trials with elbow flexor muscles by a single subject. Force generated by reference arm in black, by indicator arm in red. In the top trace, during generation of a maintained 100% MVC by the reference arm, matching forces carried out by the indicator every 15 s, overshot the reference level, as both reference and indicator force levels declined. The middle trace shows data from a similar matching experiment, but where the reference force was 35% MVC. Here, for the later matches, the matching force tended again to overshoot the reference level, the overshoot becoming significant at 5 and 10 min after the exercise. The bottom trace shows data from an experiment where the reference arm was vibrated at 80 Hz (hashed bar) during generation of a 35% MVC force. Now there was no longer any overshoot of reference force levels by the indicator, except at 5 and 10 min after the end of the contractions. Figure redrawn from Brooks et al. (2013)

of its length–tension relation (Cafarelli and Bigland-Ritchie 1979; Weerakkody et al. 2003). The experiment of Savage et al was carried out on ankle plantar flexor muscles of both legs. One muscle was held short, on the ascending limb of its length-tension relation, the muscle of the other leg, on the descending limb (Fig. 3, top panel). Ankle angles on the two sides were adjusted so that active forces in each leg corresponded to 20% MVC. The hypothesis was that if muscle stretch receptors contributed to the sense of force (Luu et al. 2011; Brooks et al. 2013), they should be more stretched in the longer muscle, so that in a matching task force generated in the longer muscle should be overestimated by force generated in the shorter muscle.

In a comparison of total force (active plus passive) between the two sides, the opposite result to that predicted was achieved; with the reference muscle held at the longer length, subjects underestimated its force level with their other leg held at a short length (Fig. 3, bottom panel). However, when passive forces were subtracted out, matching of active forces on the two sides was reasonably accurate. It appeared that subjects were responding only to the active force, that is, the effort required to generate it and they were unresponsive to the passive component. Yet in a second matching experiment, where the muscle of one leg was stretched but kept passive, and subjects were required to match its passive force with active force in the muscle of the other leg, held short enough for no passive tension to be present, they grossly overestimated the amount of active force required to match the passive force .

It was considered that in this circumstance subjects were in fact responding to two similar, but distinct senses, both appearing to arise in the test muscle, a sense of active force and a sense of passive force or of stretch. Subjects tended to assign a stronger sensation to the passive force from stretch when this was expressed as the amount of active force required to match a given level of passive force (Savage et al, Fig. 5a). Part of the reason for this difference may be that subjects generated the active force themselves, while the passive force was generated externally, by the experimenter (Shergill et al. 2003).

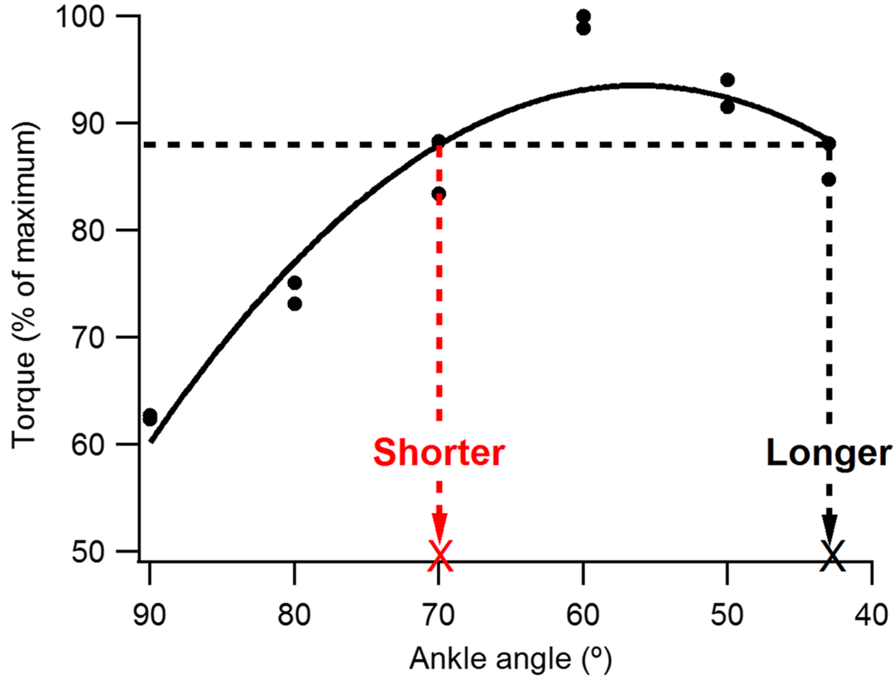
In the end, the main aim of these experiments was not achieved, to try to obtain evidence for a peripheral afferent contribution to the sense of force. It did, however, reveal a second, related sense of passive force or of stretch, likely to be of spindle origin, given the high threshold of tendon organs to passive stretch (Gregory et al. 1977) and the ability of spindles to act as passive force sensors (Blum et al. 2017). We do know that we have a stretch sense, since stretching an exposed tendon in a conscious subject produces clearly identifiable sensations (McCloskey et al. 1983). The presence of such a sense should be kept in mind when discussing the origin of the sense of force.

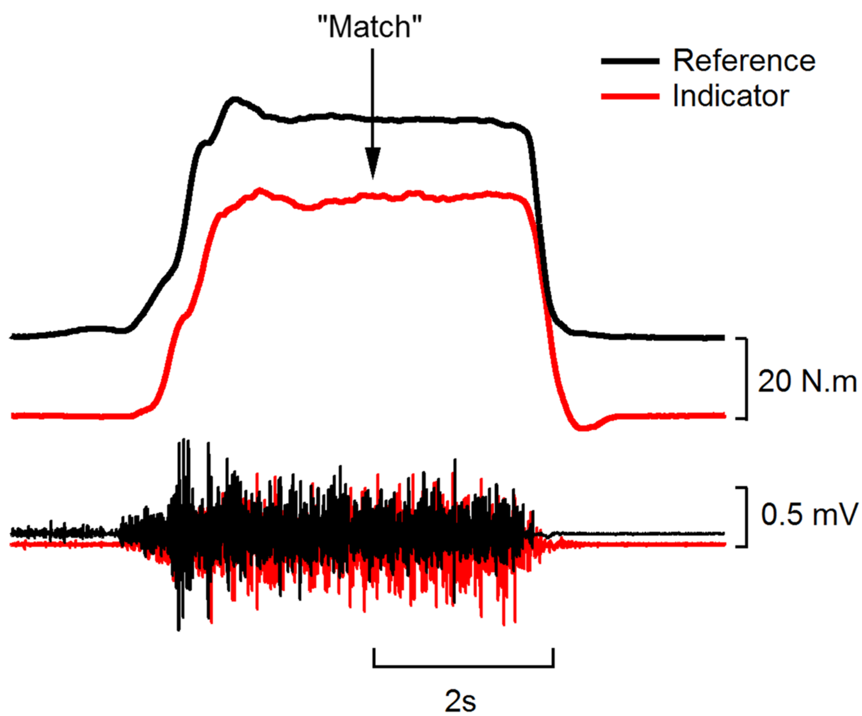
Recently, a new player has entered the field. Monjo et al. (2018) have introduced two new experimental approaches. First, they vibrated elbow flexors of the test arm for 10 min in order to desensitise peripheral afferents. Vibration was applied to the passive, stretched muscle to preferentially desensitise muscle spindles, or to a weakly contracting muscle (the extended arm supporting a 0.5 kg weight) to desensitise both spindles and tendon organs. It is known that tendon organs are very sensitive to vibration of a contracting muscle (Fallon and Macefield 2007). Subjects were required to make force matches before and after vibration conditioning. Monjo et al also introduced a new method of measurement. They argued that in a two-arm force-matching task, if Luu et al. (2011) were correct and subjects had available both a centrally generated sense of effort as well as a tension-related signal of peripheral origin, altering the effort–tension relation with fatigue or paralysis was likely to alter both central and peripheral sources of signals. In a two-arm matching task, subjects would therefore be obliged to focus on one signal or the other, leading to uncertainty in interpretation of the outcome.

In order to avoid this problem, Monjo et al asked subjects to generate a given level of muscle force, using one arm only. Subjects reported the effort required to achieve the target force, while at the same time the EMG was recorded as an indicator of the level of muscle activation. Monjo et al argued that in the one-arm test, contributions from central and peripheral sources to the sense of force were easier to distinguish.

In the experiment where the conditioning vibration was applied to the passive muscle to desensitise muscle spindles, in the two-arm matching task, following vibration conditioning, subjects made errors. The conditioned indicator undershot the target force generated by the reference arm and this was accompanied by a lower indicator EMG. The result was interpreted as supporting the action of a signal of central origin. The reduced spindle signal coming from the conditioned indicator muscle after vibration, would be expected to lower excitability of homonymous and heteronymous segmental motoneurones. Therefore, the effort signal generated centrally in order to reach the target force in the unconditioned arm would be insufficient to overcome the lower motoneurone excitability in the indicator arm, leading the subject to underestimate the reference force.

After the same conditioning delivered to the arm in a one-arm force generating task, in order to overcome the lower excitability of spinal motoneurones, a bigger central signal had to be generated to achieve the target force (under visual control). Crucially, however, subjects reported that they were able to achieve the target force with a lower applied effort than before conditioning. This was again the opposite result to what was predicted by the central hypothesis. If a central signal was involved, the





bigger central signal should have been accompanied by a bigger effort signal. It was proposed in the one-arm task that what the subject felt was a sense of effort generated by signals of muscle spindles and since vibration had reduced the spindle signal it led to a lower effort sensation.

When the second method of conditioning vibration was applied, postulated to desensitise both spindles and tendon organs, the outcome for the one-arm and two-arm tasks was in the same direction; an increase was observed in force output for a given effort in the bilateral task and a reduced effort was used to reach the target in the one-arm task. The

◀**Fig. 3** Top panel: Torque–angle curve for ankle plantar flexor muscles of a single subject. This was constructed using MVCs and active torque was determined after subtracting out any passive component. Torque (% of maximum) was plotted against included ankle angle (angle subtended between foot and shin). A decreasing angle represents a more dorsiflexed foot (stretched muscle). A Gaussian curve fit was applied to the data points, two for each angle measured, over the range 90° to 43°. Two points were identified, one on the ascending limb of the curve (red dashed line, 'Shorter'), the other on the descending limb (black dashed line, 'Longer'), where active forces were approximately the same and the corresponding ankle angles were determined (arrows). Bottom panel upper traces: Torque for the two feet of one subject generated by pushing down on a footplate to contract plantar flexors. The footplates had been set at positions corresponding to the ankle angles 'Shorter' and 'Longer' in the upper panel. At the longer length, once the subject had reached the target torque of 20% MVC (as indicated by a visual display of torque) with their reference foot (black trace), the subject was asked to match it with their other foot (red trace, no visual display) and indicate when they believed they had achieved an acceptable match by operating a switch ("Match"). The two torque records are offset due to differences in passive torque at the two joint angles. Bottom traces: Records of surface EMG from the two muscles during the voluntary contractions. Figure redrawn, in part, from Savage et al. (2015)

result was interpreted in terms of afferent actions on spinal motoneurones; desensitising spindles reduced motoneurone excitability, desensitising tendon organ reduced spinal inhibition. The nett outcome of desensitising both together was an increase in motoneurone excitability, presumably because of the greater effect of the reduced inhibition. Perhaps in a lightly loaded muscle vibration engages tendon organs more effectively than muscle spindles, leading to a more complete desensitisation of tendon organs. As a consequence, subjects required less effort to reach the target force.

The authors argued that tendon organs were not directly involved in the sense of force. In the passive vibration conditioning experiment, the vibration probably did not significantly engage tendon organs, yet significant matching errors were generated. In addition, it is known that maintaining a given level of voluntary force leads to a progressive overestimation of the force (Jones and Hunter 1983), yet such a stimulus desensitises tendon organs (Gregory and Proske 1979). Finally, tendon organs are force sensors. They will faithfully signal force changes in the muscle and therefore cannot be responsible for the disturbance to the sense of effort produced by fatigue or paralysis. So do tendon organs contribute to proprioception? Animal observations have shown that afferents of tendon organs project to the cerebral cortex of the brain (McIntyre et al. 1984). Cortical projection is a necessary prerequisite for the generation of conscious sensations. In addition, the earlier discussion of the influence of subject instruction on the outcome in force matching tasks during muscle vibration do suggest that we have available a sense of tension, presumably arising from the signals of tendon organs. It allows us to maintain constant levels of force during disturbances, a facility that is not available when we attend to the effort we apply in maintaining the force.

Monjo et al. (2018) proposed that a motor command was associated with an expectation of the sensory consequences of the movement generated. When the sensory response did not match the predictions, in circumstances such as during fatigue or paralysis, the brain might weigh up the two sources of afferent information, that predicted and what was actually perceived, to form an estimate lying somewhere in between (Franklin and Wolpert 2011).

Concluding comments

Putting all of the recent evidence together, it can be concluded that for the senses of effort, force and heaviness, subjects have available two sources of information, a centrally generated signal and a peripheral signal. The peripheral signal will typically arise in the test muscle, but it may also involve receptors in overlying skin (Gandevia et al. 1980).

Monjo et al. (2018) make the point that for the senses of force and heaviness the origin of the proprioceptive signal is task dependent. They propose that when subjects use one arm to generate a given level of force, the dominant signal is coming from muscle spindles, while in a two-arm matching task it is difficult to untangle the contributions from central and peripheral sources, although it is likely that both are contributing. This situation is similar to that reported by Tsay et al. (2016), who showed that in a two-arm position-matching task, signals of muscle spindles provided the positional signal. They went on to show in a one-arm experiment, where the subject was required to use a pointer to indicate the perceived position of their hidden arm, the evidence no longer supported a role for muscle spindles as the principal position sensors and signals from other sources, perhaps skin and joints, provided the positional information. So this is another example of task-dependency.

However, there is one important difference between the two-arm force-matching and two-arm position-matching experiments. In position matching, it was proposed that spindle signals from both arms were being compared and that the brain computed their difference to determine the matching outcome (Proske and Gandevia 2018). Such a "difference mechanism" is obviously not available in the one-arm position sense measurement and it was necessary for other sources of signal to provide the information. In force matching (Monjo et al. 2018), why should there be a switch from accessing two sources of signal in a two-arm test to only one source in the one-arm test? Perhaps in the two-arm test the central signal is used as part of a comparison mechanism, similar to that postulated for position sense. It remains for future experiments to reveal the reason for this shift in strategy. Finally, as we have all experienced, carrying a heavy suitcase for a time gives the impression it is becoming heavier, not lighter. Yet we typically carry the suitcase with one hand. So, clearly, in a one-arm heaviness task there is the suggestion of the operation of a central influence.

The studies of Luu et al. (2011) and of Brooks et al. (2013) suggest that to obtain evidence for a peripheral afferent contribution to the senses of force and heaviness, it is necessary to produce severe fatigue using MVCs or use submaximal contractions in combination with vibration. Alternatively, the muscle is subjected to prolonged conditioning vibration (Monjo et al. 2018). Against the background of our everyday experience that fatigued limb muscles make objects feel heavier and require more effort to lift, it suggests that the centrally generated effort signals operate early during the fatigue process where muscle force is falling, but can still be recovered by an increased motor command. As fatigue intensifies, the strength of peripheral afferent signals falls, leading to a transition from a sensation of increased heaviness to one of a lighter load. In the future, evidence should be sought for such transitions in sensation by carefully grading fatigue or paralysis levels.

One remaining question concerns the role of spindles as force sensors. During a voluntary contraction, how accurately can a rise in spindle discharge from fusimotor co-activation (Vallbo 1971, 1974) indicate the level of force? It is known that spindles respond promptly at the onset of a voluntary contraction and the majority are recruited by 3% MVC (Wilson et al. 1997). Presumably at levels above 3% spindles have the capacity to increase discharge levels further by means of intrafusal rate coding. However, as the contraction rises there is the growing likelihood of spindle unloading effects from the contracting muscle fibres. While the full range of the relationship between spindle discharge rates and motor unit recruitment levels is not known, there is evidence that less than half of the motor units would be recruited at a point where all spindles were co-activated (Allen et al. 2008). This is another point for further study in the future.

Finally, there has been some debate over the relatively few roles that have so far been able to be attributed to the fusimotor system in motor control (Proske and Gandevia 2018). While there is evidence for involvement of the fusimotor system in certain learned tasks (see, for example, Dimitriou 2016), its role in force sense represents a new and important contribution to proprioception.

Summary

The sense of effort

This is believed to be generated centrally, by transmission of an efference copy of the motor command to sensory areas (Fig. 1). The evidence suggests that the sense of effort is linked to the sense of force by how subjects are instructed. Subjects have the ability to select between a sense of effort and a sense of force. The sense of effort is responsible for the commonly perceived increases in heaviness after muscle fatigue or paralysis. Recent evidence suggests that in a one-arm force generating task, the effort sensation is generated by peripheral receptors.

The sense of force or of tension

This is believed to be generated by peripheral receptors, including both muscle spindles and tendon organs (Fig. 1). It can be selectively engaged by appropriately instructing subjects. During fatigue, if it is sufficiently severe, there is evidence of a contribution from muscle spindles to the sense. We also have a sense of passive force or of stretch. Here the afferent signals are not likely to be coming from tendon organs which are relatively insensitive to passive forces. More likely, stretch of passive spindles, as well as, perhaps, signals from skin receptors are responsible.

The sense of heaviness

The evidence suggests that this can be generated both centrally and by peripheral afferent activity (Fig. 1). The sense is unique in that its perception is most acute during movement. The senses of effort and heaviness are linked since during muscle fatigue or paralysis, we perceive both a sense of increased heaviness and an increase in effort. If fatigue is sufficiently severe, objects feel lighter rather than heavier. Here evidence from muscle vibration and from muscle paralysis supports a contribution from muscle spindles to the sense of heaviness.

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