

Kinesthetic Sensing

Lynette A. Jones
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA

The term kinesthesia refers to the perception of limb movement and position, and is often broadly defined to include the perception of force as well. These sensory perceptions originate primarily from the activity of mechanoreceptors in muscles, which provides the central nervous system with information about the static length of muscles, the rate at which muscle length changes, and the forces muscles generate. From these signals comes our awareness of where our limbs are in space, when our limbs have moved, and the mechanical properties of objects (e.g. weight, compliance) with which they interact. Sensory information about changes in limb position and movement also arises from other sources, namely receptors in the skin and joints. These inputs appear to be particularly important for kinesthesia in the hand, as both joint (Clark et al., 1989; Ferrell et al., 1987) and (or) cutaneous anesthesia (Clark et al., 1986) impairs the ability to detect finger movements and perceive finger positions. For more proximal joints, such as the knee, joint and (or) skin anesthesia does not have a significant influence on the perception of limb position (Clark et al., 1979). It appears that for the hand, cutaneous receptors provide an important facilitatory input to the central nervous system that is used to interpret position and movement signals arising from other sources. Cutaneous receptors in the hairy skin on the dorsum of the hand are capable, however, of encoding joint movement very precisely via their responses to stretch of the skin overlying the active joint (Collins & Prochazka, 1996; Edin, 1992). The importance of cutaneous sensory feedback to the perception of finger movements and positions is not surprising in view of the high innervation density of cutaneous mechanoreceptors in the hand, and its specialization for tactile exploration and manipulation. This feedback may also be more important for kinesthesia in the hand than for other parts of the body because of the complex anatomical arrangement of muscles, with most muscles acting over several finger joints, which would result in a considerable ambiguity of muscle spindle receptor discharges. In addition to these peripherally originating signals, there is evidence that central (cortical) feedback pathways provide information that is used to decode muscle afferent signals and in the perception of force.

Sensory Receptors

The mechanoreceptors found in muscles, known as the primary and secondary spindle receptors, are located in muscle spindles, which are elongated structures ranging from 0.5 to 10 mm in length, composed of bundles of small intrafusal muscle fibers. The spindles lie in parallel to the extrafusal muscle fibers, the force-producing component of muscle, and attach at both ends to either the extrafusal fibers or to muscle tendons. Due to their position in muscles, spindles are specifically responsive to changes in muscle length (Hulliger, 1984). Muscle spindles have their own motor innervation via the fusimotor or gamma

system and some spindles are also innervated by skeletofusimotor fibers that go to both extrafusal and intrafusal muscle fibers. One of the functions of the fusimotor system is to regulate the sensitivity of muscle spindles. It can cause the firing rates of spindle receptors to increase at a given muscle length ('bias') and can also control the sensitivity of the receptors to changes in muscle length ('gain').

Both types of spindle receptor respond to changes in muscle length, but primary spindle receptors are much more sensitive to the velocity and acceleration component of a lengthening contraction, and increase their discharge rates considerably as the velocity of the stretch increases. Primary spindle receptors are, however, highly nonlinear and their discharge rates depend on several factors including the length of the muscle, its recent contractile history, the actual velocity with which the muscle is changing length and the activity of the fusimotor system. Secondary spindle receptors show much less dynamic responsiveness and have a more regular discharge rate than primary receptors at a constant muscle length (Prochazka, 1996). The higher dynamic sensitivity of primary spindle receptors has been interpreted as indicating that they signal the velocity and direction of muscle stretch or limb movement, whereas the secondary spindle receptors provide the central nervous system with information about static muscle length or limb position.

For the tactile system, higher densities of mechanoreceptors (e.g. in the fingertips and around the mouth) are clearly associated with superior tactile acuity. This does not appear to be the case for the kinesthetic system where the overall number of receptors is much smaller (25,000-30,000 muscle spindles in the human body, with 4,000 in the muscles in each arm as compared to 17,000 cutaneous mechanoreceptors in the human hand alone) and higher densities are not clearly associated with superior kinesthetic abilities. Spindle density appears to depend more on muscle size rather than function (Prochazka, 1996). The number of spindles in human muscles varies and for muscles in the arm has been estimated to range from 34 for the first dorsal interosseus, an intrinsic muscle of the hand, to 320 in the biceps brachii, an elbow flexor (Buchthal & Schmalbruch, 1980). When expressed in terms of the number of spindles per gram of mean weight of adult muscle, high spindle densities are found in the intrinsic hand muscles and the highest densities are reported for the deep layers of neck muscles where densities of up to 500 spindles/g have been found.

The third type of mechanoreceptor found in muscle is the Golgi tendon organ, an encapsulated receptor about 1 mm long and 0.1 mm in diameter, normally found at the junction between the muscle tendon and a group of 10-20 extrafusal muscle fibers. The receptor is therefore said to be "in-series" with this group of muscle fibers, is selectively responsive to the forces they develop and has little or no response to the contraction of other muscle fibers (Jami, 1992). Golgi tendon organs are very sensitive to the in-series forces, and most tendon organs in a muscle will discharge in all but the smallest contraction. The number of tendon organs in different muscles varies considerably, and some muscles such as the lumbrical muscle of the hand do not appear to have any tendon organ receptors. Their numbers should not be equated with a muscle's involvement in fine motor control. Golgi tendon organ receptors are always less frequent and more variable in number than spindle receptors (Devanandan et al., 1983).

Perception of Limb Movement and Position

Psychophysical studies of the kinesthetic system usually focus on three variables: the perception of limb position, limb movement and force. The ability to detect movements of a limb depends on several factors including the velocity of the movement, the particular joint moving, and the contractile state of the muscles controlling the joint. Faster movements are easier to detect than slower movements, and for the distal joints of the fingers, thresholds decrease from 8° to 1° as the movement velocity increases from $1.25^\circ/\text{s}$ to $10^\circ/\text{s}$. The threshold then remains essentially constant at 1° over the velocity range of $10\text{-}80^\circ/\text{s}$ (Hall & McCloskey, 1983). Movements of proximal joints such as the elbow or shoulder are easier to detect than movements of the same amplitude made by more distal joints such as the metacarpophalangeal joints at the base of the fingers in the hand as shown in Figure 1 (Hall & McCloskey, 1983). This superior performance of more proximal joints is not surprising given that they move more slowly than distal joints, and that rotation of these joints results in a larger displacement of the end-point of the limb than the same angular rotation at a more distal joint. For example, when the shoulder rotates 1° the middle fingertip of the outstretched arm moves 13 mm, whereas a 1° rotation of the distal interphalangeal joint of the middle finger results in only a 0.5 mm movement of the fingertip.

Movement thresholds also decrease if the movement is imposed while the muscles acting on the joint are actively contracting rather than relaxed. For the elbow flexor muscles, the threshold for detecting movements can be up to ten times smaller if the muscles are contracting when the movement is imposed on the joint as can be seen in Figure 1 (Taylor & McCloskey, 1992). This effect is greatest at lower movement velocities, which suggests that the enhanced level of muscle spindle afferent activity that occurs when a muscle contracts facilitates the detection of a movement.

When we move our arms or legs we are aware that the position of the limb has changed, and so there is a perception of both limb movement and limb position. It has been possible to separate these two aspects of perception experimentally by imposing extremely slow movements on a joint (i.e. $1\text{-}4^\circ/\text{min}$) that result in a change in the position of the joint in the absence of any awareness that a movement has occurred. Using this procedure, it has been shown that people can make independent judgments of the position and movement of a limb (Clark et al., 1985). In contrast to the sense of limb movement, the ability to detect a change in the position of a limb is not affected by the angular velocity of the movement, but does depend on the absolute position of the limb and on the specific joint moved. Taylor and McCloskey (1990) reported that the threshold for detecting a change in the position of the joints of the hand ranges from 4.4° for the metacarpophalangeal joint, to 6.8° for the proximal interphalangeal joint. These thresholds were obtained using movement velocities of less than $2^\circ/\text{min}$ so subjects could not perceive that their fingers had moved. Using a different experimental paradigm, Tan et al. (1994) reported that the thresholds for these two finger joints were smaller and averaged 2.5° . Consistent with the findings on the perception of limb movement, the position resolution of joints varies in a distal to proximal order, with proximal joints having a superior position resolution than more distal joints (Clark et al., 1995; Tan et al., 1994).

The perception of limb position is often measured using a matching procedure in which the subject is asked to align the positions of two corresponding joints on the left and right sides of the body in the absence of any visual feedback about limb position. It is generally accepted that the limiting factor of performance on this type of task is imposed by the sensory input and not the motor capacity of the subject to achieve the target position, although clearly errors can arise from both sources. The errors in matching the positions of two corresponding joints in the absence of vision are often surprisingly large. For example, when subjects match the positions of the proximal interphalangeal joints of the left and right index fingers errors range from 0.75 to 6° over a range of 100-175° of finger flexion (Clark et al., 1995). The errors in matching the position of two limbs increase with time (for the hand errors increase from 16 to 30 mm over a 120 s time interval), indicating that without visual input for recalibration the kinesthetically perceived position of a limb drifts (Wann & Ibrahim, 1992). Acuity is better, however, if subjects move their limbs actively to a position rather than having the experimenter move a passive limb, but is not improved if the muscles contract after the limb has moved. This result is consistent with the findings on the perception of movement where it was noted that muscle contraction enhanced the detection of limb movements. With active positioning, the errors in matching the positions of the outstretched arms average 0.6°, as compared to 2° when the limb is moved passively (Paillard & Brouchon, 1968).

The movement and position thresholds described above refer to the smallest amount of stimulus energy that is detected, and are known as the absolute thresholds. It is also of interest to know the increment or decrement in stimulation required for a person to discriminate that a change has occurred. The latter is known as the differential threshold or just noticeable difference (jnd) and when expressed as a percentage is dimensionless and can be compared across different sensory processes. The differential threshold for limb movement has been estimated to be 8% for the elbow joint (Jones et al., 1992) and for finger and elbow joint position averages 8% (range: 3-11%) (Clark et al., 1995). This means that there must be at least an 8% change in the amplitude of a movement delivered to a limb or in the position of a limb for a person to perceive that a change has occurred. The differential threshold for limb position is also the absolute threshold in that there is no zero point for position, as the joint must always move from a reference position.

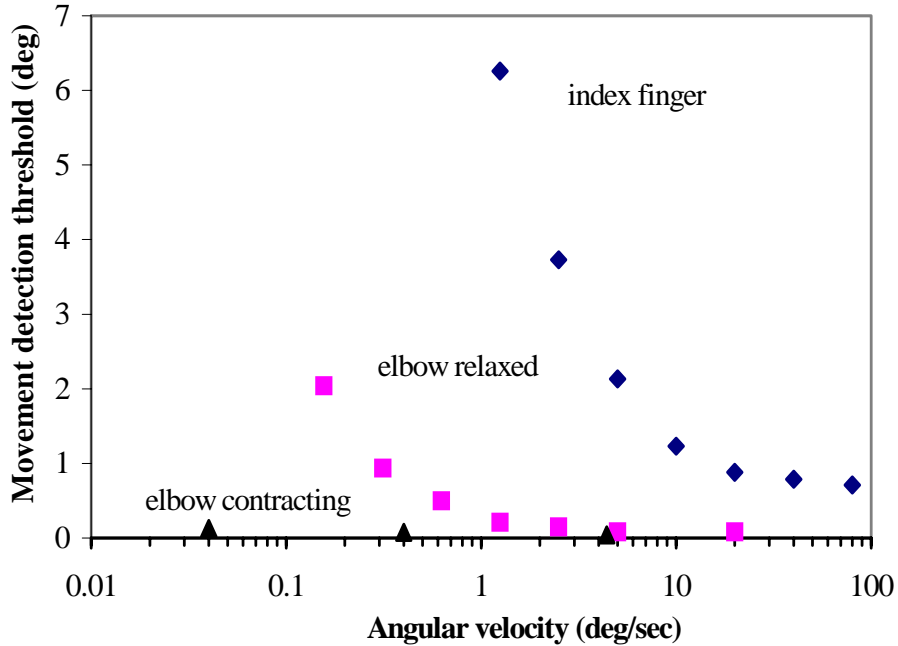


Figure 1. Movement detection thresholds measured for the index finger [diamonds] and elbow joint [squares] (Hall & McCloskey, 1983) under passive conditions, and while the elbow flexor muscles are generating force [triangles] (Taylor & McCloskey, 1992).

Another performance measure for the perception of limb movement and position is the accuracy with which a movement or position can be reproduced. The errors associated with reproducing the amplitude of an active finger movement average 3° over a wide range of amplitudes. The ability to reproduce a target position of a limb is less precise and errors are typically in the order of $5\text{-}9^\circ$ over the full range of finger joint movement. The number of positions that can be independently resolved for a given joint has also been measured and follows the distal to proximal gradient described for thresholds, with a superior resolution reported for more proximal joints (Clark et al., 1995).

Perception of Force

There are two sources of information about the forces generated by muscles. First, afferent discharges from Golgi tendon organs signal intramuscular force and therefore provide the central nervous system with information about the forces produced by muscles. Second, force information could be derived from an internal neural correlate or copy of the motor command (sometimes referred to as corollary discharges) sent to the motor neuron pool in the spinal cord. This signal is probably transmitted to the sensory centers in the brain and may reflect the magnitude of the descending motor signal. The results from several experiments indicate that whenever there is an increase in the motor command sent to a muscle there is a corresponding increase in the perceived magnitude of the force of contraction, even when the force exerted by the muscle remains constant. For example, when subjects are required to estimate the magnitude of a force maintained at a constant

amplitude until the point of maximal endurance is reached when the muscle is completely fatigued, there is a linear increase in the perceived amplitude of sustained force (Jones & Hunter, 1983). In this situation, as the force is maintained the centrally generated neural input required to produce the force increases as the muscle fatigues. It seems unlikely that the overestimation of force is based on discharges arising from Golgi tendon organs in the muscle as these would remain constant or decrease (if they adapt) while the muscle continued to generate a constant force.

The change in force that a human operator can reliably discriminate is a function of the current level of force being produced by the operator or fed back through a device such as a haptic interface. The differential threshold for force averages 7-10% over a force range of 0.5-200 N, and appears to be consistent across a wide variety of muscle groups. Discrimination deteriorates for forces smaller than 0.5 N, with the threshold now increasing to 15-27%. Forces as small as 0.14 and 0.2 N can still, however, be distinguished. A summary of the thresholds for limb position, movement, force and variables derived from these is presented in Table 1.

Table 1: Perceptual characteristics of kinesthetic system

Variable	Resolution	Differential threshold
Limb movement	0.5-1° (over 10-80°/s range)	8% (range: 4-19%)
Limb position	0.8-7° (full range of motion)	7% (range: 5-9%)
Force	0.06 N	7% (range: 5-12%)
Stiffness	Not available	17% (range: 8-22%)
Viscosity	Not available	19% (range: 14-34%)
Inertia	Not available	28% (range: 21-113%)

Forces produced by muscles controlling the fingers can be reproduced reasonably accurately. The errors in reproducing the force of a pinch grasp involving the thumb and index finger range from 1.25 to 3.75 N for target forces between 2.5 and 18.75 N (Mai et al., 1991). When expressed in relative terms these errors are large at low force levels (i.e. around 50%), but in absolute terms are small (1.25 N) and suggest that the kinesthetic system is reasonably precise in its capacity to reproduce a target force. The accuracy with which the index finger can maintain a force at a constant amplitude through time using only kinesthetic and tactile (i.e. haptic) feedback has also been measured and compared to force control when visual feedback about the force is also provided. Over a 120-s time interval it was found that the mean absolute error did not differ significantly between the haptic feedback and visual feedback conditions and averaged 0.26 N for forces ranging from 2-6 N. The variability in force control was, however, greater when only haptic feedback was available and averaged 11% with haptic feedback as compared to 6% when visual feedback was also provided.

Perception of Stiffness, Viscosity and Inertia

The kinesthetic system is not only involved in processing information regarding the forces generated by muscles and the associated movements of limbs, but also uses this information to derive cues about other variables such as stiffness, viscosity and inertia for which there are no known peripheral sensors. The perception of these latter variables is particularly relevant to the design of interfaces that human operators use to control remote devices in that the mechanical properties of the interface can have a profound effect on operator performance. In addition in many environments in which haptic interfaces will be used, such as inside the human body or in undersea environments, accurate perception of mechanical properties such as tissue stiffness is important to task performance.

Studies of the perception of stiffness and viscosity indicate that there is a loss in perceptual resolution when force and displacement or force and velocity cues are combined to perceive the stiffness or viscosity of a mechanical system. The differential thresholds for stiffness range from 8-22% (Jones & Hunter, 1990a; Tan et al., 1995) and for viscosity range from 14-23% (Beauregard et al., 1995; Jones et al., 1997), which are considerably higher than the differential thresholds measured for limb movement, position and force all of which are between 6-8% (Jones et al., 1992; Tan et al., 1995). Variations in the thresholds measured reflect differences in the conditions under which subjects perceive stiffness (K) or viscosity and in the psychophysical procedures used. For example, in their study of the perception of compliance ($1/K$) of a rigid system, Tan et al. (1995) constrained their subjects to move over a fixed displacement and so the subjects were able to use terminal force cues to estimate the compliance of the mechanical system. Under these conditions the average threshold was calculated to be 8%, which is the differential threshold for force. When the displacement was randomized from trial to trial so that terminal force cues were no longer correlated with compliance, threshold estimates increased and now the average threshold for compliance was found to be 22%.

Threshold estimates are also a function of the psychophysical method used as the criterion for calculating a threshold varies with different procedures. For example, when the differential threshold for viscosity was measured using a matching paradigm in which subjects adjusted the viscosity of one mechanical system connected to their arms until it was the same as that of the system connected to the contralateral limb, the threshold for viscosity was calculated to be 34% (Jones & Hunter, 1993). However, when a two alternative force-choice procedure was used to measure the differential threshold for viscosity which requires that subjects indicate which of two mechanical systems has the greater viscosity, the threshold was now calculated to be 19% (Jones et al., 1997). The matching method, known as the method of adjustment, uses a criterion of 84% correct to calculate the threshold, whereas the two-alternative forced choice procedure calculates a threshold at the 71% correct level. By conversion of the threshold values it can be shown that these thresholds form a line that goes through the origin, which suggests that they arise from the same underlying process.

There have been relatively few studies of the perception of inertia, although preliminary results indicate a relatively poor sensitivity to changes in inertia, consistent with the findings on stiffness and viscosity. Beauregard et al. (1995) reported that the

threshold for discriminating changes in mass was 21%, whereas differential thresholds for the moment of inertia of hand-held objects have been found to range from 28% to 113% (Ross & Benson, 1986). The latter appear to be dependent on the range of inertias presented to subjects which suggests that this perceptual dimension may not follow Weber's law (i.e. a linear relation between the size of the differential threshold and the reference stimulus amplitude).

Neuromuscular System

The resolution of the kinesthetic system described above with respect to movement, position and force reflects its perceptual processing capabilities which may be quite different from the resolution achieved in the performance of a task. Many highly skilled manual activities such as microsurgery and micro-electronic assembly are performed under visual control, usually through an operating microscope, and the movements and forces produced are usually not perceived kinesthetically. These movements are typically very small (150-200 μm), and performed slowly. Voluntary movements involving the hand and arm are generally performed within a peak frequency range of 1-8 Hz, and even very rapid movements such as those produced when typing or piano playing have peak frequencies in the 4-8 Hz range (Kunesch, et al., 1989). The bandwidth of voluntary motor responses has also been measured using a variety of stimuli that subjects track by moving their arm or hand, and the results from these studies generally show maximum bandwidths of between 2 to 5 Hz (Cathers et al., 1996). On the basis of these analyses of voluntary movements it would appear that for the human kinesthetic system the displacement-input bandwidth is approximately 0-12 Hz.

The bandwidth for controlling forces has been estimated to be approximately 2 Hz when calculated from the impulse response function measured using force-tracking data from the forearm (Jones & Hunter, 1990b). The decrease in the inertia of the fingers as compared to the arm would result in a slightly higher estimate of the bandwidth for force control of the fingers but it would still be less than 6 Hz.

Research Challenges

Much of what is known about the human kinesthetic system is based on the use of stimuli that are sub-optimal in terms of the response properties of peripheral sensors. One of the features of the kinesthetic system that distinguishes it from other sensory systems is that much of the information that it processes is self-produced and not the result of external stimulation. Despite this, most threshold estimates for movement and position are derived using passive movements imposed on a limb. It is known that limb movement thresholds depend on the velocity of the movement, and that these thresholds can decrease by an order of magnitude at some movement velocities if the muscles acting on the joint being moved are contracting when the movement is imposed (Taylor & McCloskey, 1990). It is clear that the experimental use of more natural stimuli (self-produced) would provide a better understanding of the properties of the kinesthetic system.

One feature of research in kinesthesia that distinguishes it from work on the tactile sensory system is the absence of a strong tradition of coupling neurophysiological with psychophysical experimentation. This partly reflects the considerable problems associated with interpreting neural activity from muscle receptors, whose discharge rates are a complex function of the length of the muscle, whether is it shortening or lengthening, the level of fusimotor activity, and the muscle's recent contractile history. Improvements in the techniques used to record and analyze neurophysiological data from muscle receptors and fusimotor neurons would greatly enhance our understanding of the peripheral neural codes processed by the kinesthetic system.

References

- Beauregard, G.L., Srinivasan, M.A., & Durlach, N.I. (1995). The manual resolution of viscosity and mass. *Proceedings of the ASME Dynamic Systems and Control Division DSC Vol 57-2*, 657-662.
- Buchthal, F. & Schmalbruch, H. (1980). Motor unit of mammalian muscle. *Physiological Reviews*, 60, 90-142.
- Cathers, I., O'Dwyer, N., & Neilson, P. (1996). Tracking performance with sinusoidal and irregular targets under different conditions of peripheral feedback. *Experimental Brain Research*, 111, 437-446.
- Clark, F.J., Horch, K.W. Bach, S.M. & Larson, G.F. (1979). Contribution of cutaneous and joint receptors to static knee-position sense in man. *Journal of Neurophysiology*, 42, 877-888.
- Clark, F.J., Burgess, R.C., Chapin, J.W., & Lipscomb, W.T. (1985). Role of intramuscular receptors in the awareness of limb position. *Journal of Neurophysiology*, 54, 1529-1540.
- Clark, F.J., Burgess, R.C., & Chapin, J.W. (1986). Proprioception with the proximal interphalangeal joint of the index finger. *Brain*, 109, 1195-1208.
- Clark, F.J., Grigg, P. & Chapin, J.W. (1989). The contribution of articular receptors to proprioception with the fingers in humans. *Journal of Neurophysiology*, 61, 186-193.
- Clark, F.J., Larwood, K.J., Davis, M.E. & Deffenbacher, K.A.(1995). A metric for assessing acuity in positioning joints and limbs. *Experimental Brain Research*, 107, 73-79.
- Collins, D.F. & Prochazka, A. (1996). Movement illusions evoked by ensemble cutaneous input from the dorsum of the human hand. *Journal of Physiology*, 496, 857-871.
- Devanandan, M.S., Ghosh, S., & John, K.T. (1983). A quantitative study of muscle spindles and tendon organs in some intrinsic muscles of the hand in the bonnet monkey (*Macaca radiata*). *Anatomical Record*, 207, 263-266.
- Edin, B.B. (1992). Quantitative analysis of static strain sensitivity in human mechanoreceptors from hairy skin. *Journal of Neurophysiology*, 67, 1105-1113.
- Ferrell, W.R., Gandevia, S.C. & McCloskey, D.I. (1987). The role of joint receptors in human kinesthesia when intramuscular receptors cannot contribute. *Journal of Physiology*, 386, 63-71.
- Hall, L.A., & McCloskey, D.I. (1983). Detections of movements imposed on finger, elbow and shoulder joints. *Journal of Physiology*, 335, 519-533.
- Hulliger, M. (1984). The mammalian muscle spindle and its central control. *Reviews of Physiology, Biochemistry, and Pharmacology*, 101, 1-110.

- Jami, L. (1992). Golgi tendon organs in mammalian skeletal muscle: Functional properties and central actions. *Physiological Reviews*, 72, 623-666.
- Jones, L.A. & Hunter, I.W. (1983). Effect of fatigue on force sensation. *Experimental Neurology*, 81, 640-650.
- Jones, L.A. & Hunter, I.W. (1990a). A perceptual analysis of stiffness. *Experimental Brain Research*, 79, 150-156.
- Jones, L.A. & Hunter, I.W. (1990b). Influence of the mechanical properties of a manipulandum on human operator dynamics. *Biological Cybernetics*, 62, 299-307.
- Jones, L.A. & Hunter, I.W. (1993). A perceptual analysis of viscosity. *Experimental Brain Research*, 94, 343-351.
- Jones, L.A., Hunter, I.W., & Irwin, R.J. (1992). Differential thresholds for limb movement measured using adaptive techniques. *Perception & Psychophysics*, 52, 529-535.
- Jones, L.A., Hunter, I.W., & Lafontaine, S. (1997). Viscosity discrimination: A comparison of an adaptive two-alternative forced-choice and an adjustment procedure. *Perception*, 26, 1571-1578.
- Kunesch, E., Binkofski, F., Freund, H.-J. (1989). Invariant temporal characteristics of manipulative hand movements. *Experimental Brain Research*, 78, 539-546.
- Mai, N., Schreiber, P., & Hermsdorfer, J. (1991). Changes in perceived finger force produced by muscular contractions under isometric and anisometric conditions. *Experimental Brain Research*, 84, 453-460.
- Paillard, J. & Brouchon, M. (1968). Active and passive movements in the calibration of position sense. In Freedman, S.J. (Ed), *The Neuropsychology of Spatially Oriented Behavior*. Homewood, Dorsey Press, pp. 37-55.
- Prochazka, A. (1996). Proprioceptive feedback and movement regulation. In Rowell, L., Shepherd, J.T. (eds): *Handbook of Physiology. Section 12. Exercise: Regulation and Integration of Multiple Systems*. New York, American Physiological Society, pp 89-127.
- Ross, H.E., & Benson, A.J. (1986). The Weber fraction for moment of inertia. In B. Berglund, U. Berglund, & R. Teghtsoonian (Eds.), *Fechner Day 86* (pp. 71-76). Stockholm: International Society for Psychophysics.
- Tan, H.Z., Eberman, B., Srinivasan, M.A., & Cheng, B. (1994). Human factors for the design of force-reflecting haptic interfaces. *Proceedings of the ASME Dynamic Systems and Control Division DSC Vol 55-1*, 353-359.
- Tan, H.Z., Durlach, N.I., Beauregard, G.L., & Srinivasan, M.A. (1995). Manual discrimination of compliance using active pinch grasp: The roles of force and work cues. *Perception & Psychophysics*, 57, 495-510.
- Taylor, J.L., & McCloskey, D.I. (1992). Detection of slow movements at the elbow during active flexion in man. *Journal of Physiology*, 457, 504-513.
- Wann, J.P. & Ibrahim, S.F. (1992). Does limb proprioception drift? *Experimental Brain Research*, 91, 162-166.