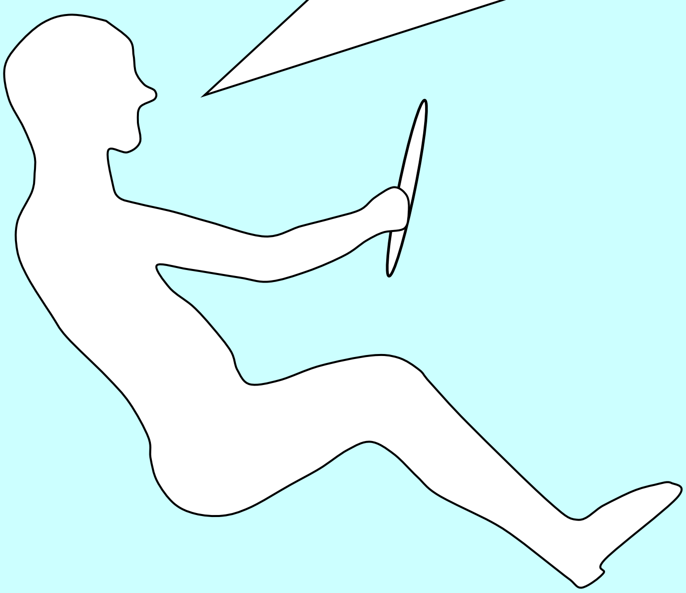
University of Sheffield

Human Perception of Hand Arm Vibration



A Seminar Presented at the COREP

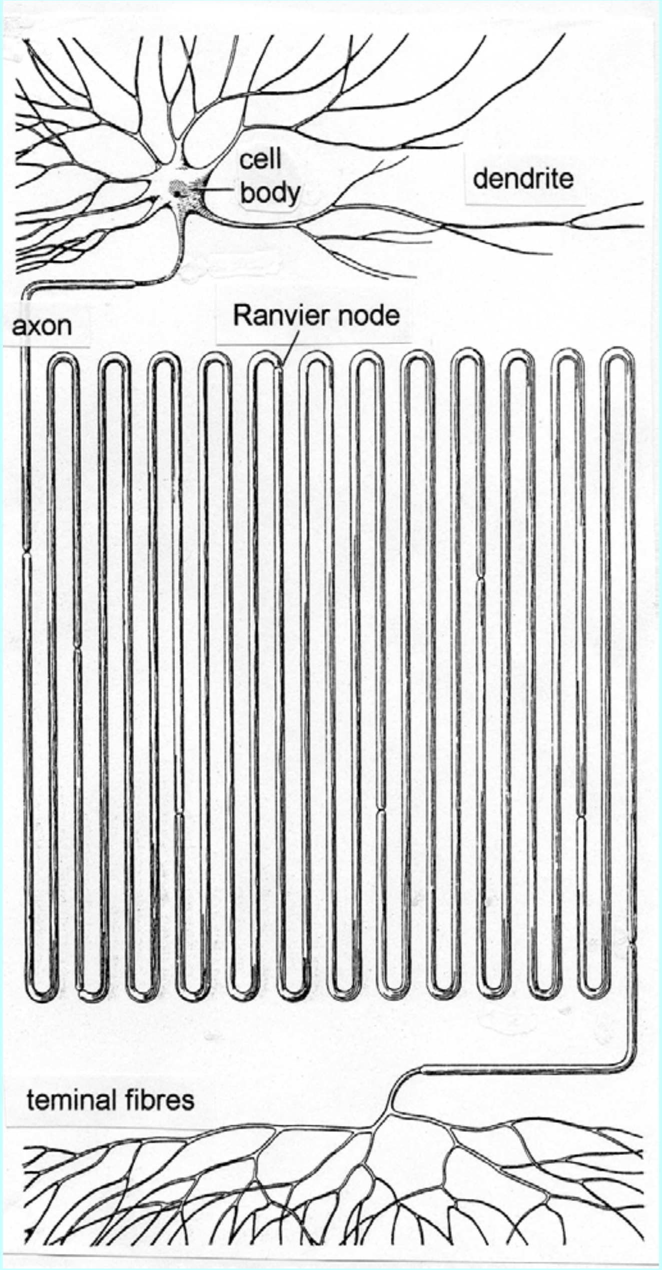
8/7/2002

The Neuron

Neurons are monocellular structures which act as the building blocks of the nervous system. It is estimated that the brain alone is composed of at least 10^{11} neurons.

Electro-chemical impulses either originate at the cell body (in he case of a receptor cell) or arrive at the neuron from dendritic synapses. The impulse then propagates along the axon and is passed to successive neurons through synapses at the axon terminations.

Dendrites (inputs) and the axon terminations (outputs) can form synapses with tens or thousands of other neurons.



The length of a neuron's axon can be from a few millimetres to more than a meter depending on the specific cell. Many axons such as the one illustrated here are surrounded by a myelin sheath which is discontinuous at points called Ranvier Nodes.

Receptors

A receptor is a special nervous cell (neuron) which is capable of transforming energy from one form to another.

A receptor typically transforms ambient energy into electro-chemical energy associated with the polarisation of the receptor’s membrane.

Receptors normally transform several types of incident energy, but one will have the lowest threshold value. This makes it possible to distinguish specific receptors for the various forms of energy.

Sensory Systems

Receptors are the point of contact between the nervous system and the outside world. They form part of sensory systems which extract information from the energy incident upon the body. The information extracted includes:

- stimulus modality
- stimulus intensity
- stimulus duration
- stimulus location

Sensory Systems

Modality	Stimulus	Receptor Types	Receptors
vision	light	photoreceptor	rods and cones
audition	sound	mechanoreceptor	hair cells (cochlea)
balance	head motion	mechanoreceptor	hair cells (semicircular canals)
somatic	mechanical thermal chemical	mechanoreceptor thermoreceptor nociceptor chemoceptor	dorsal root ganglion neurons
taste	chemical	chemoreceptor	taste buds
smell	chemical	chemoreceptor	olfactory sensory neurons

Somatic Sensory System

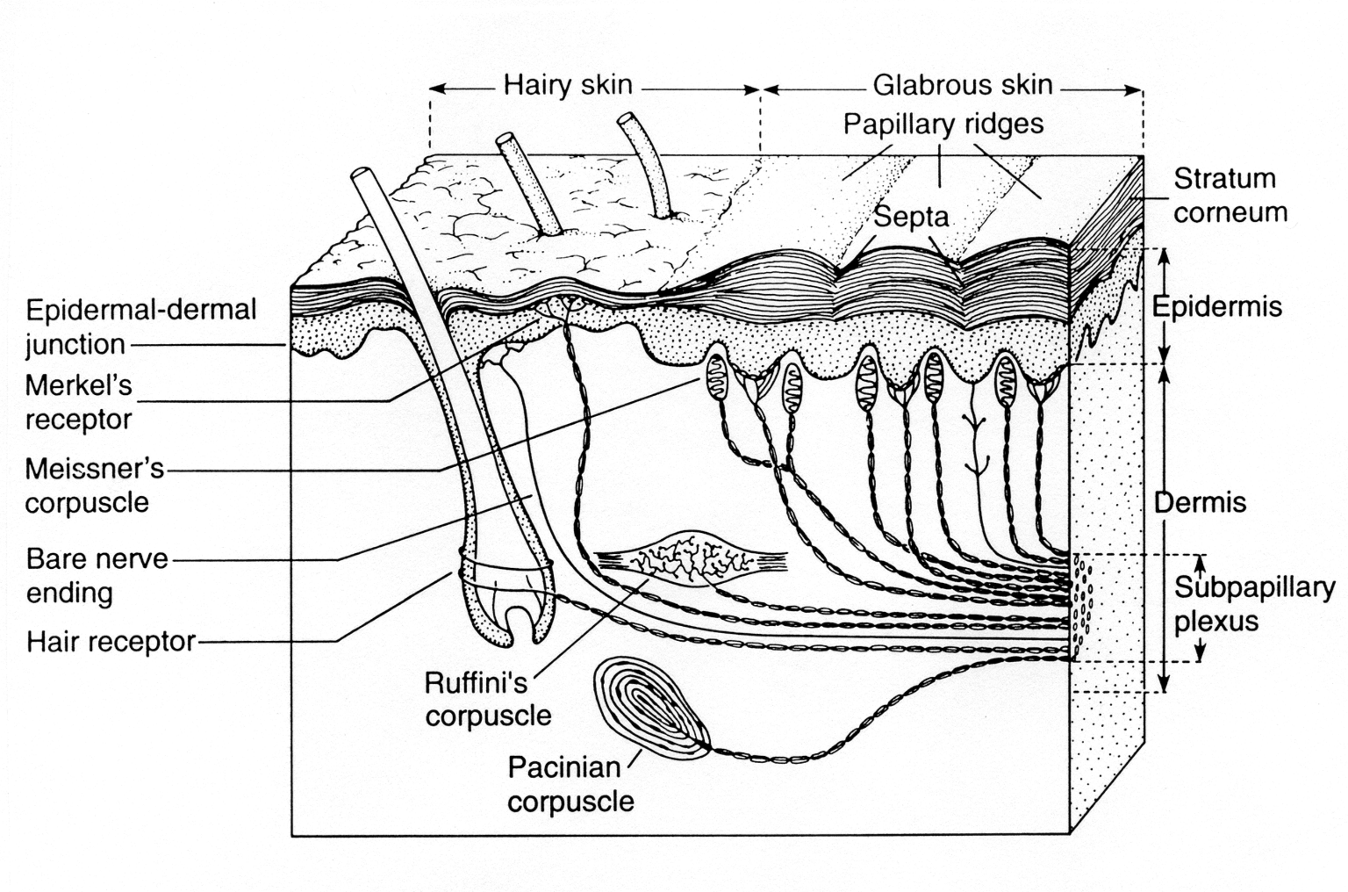
The somatic system is different from other sensory systems in that the sensors are distributed throughout the body rather than concentrated in a specific, localised organ. For this reason somatic perception is often called the body sense.

Somatic Sensory System

The somatic system processes stimuli from many types of receptors. A variety of sensations are produced, the four most important being:

- **touch** → produced by mechanical stimulation of the body surface
- **proprioception** → produced by mechanical displacements of the muscles and joints
- **pain** → produced by tissue damaging stimuli
- **thermal** → produced by cool or warm stimuli

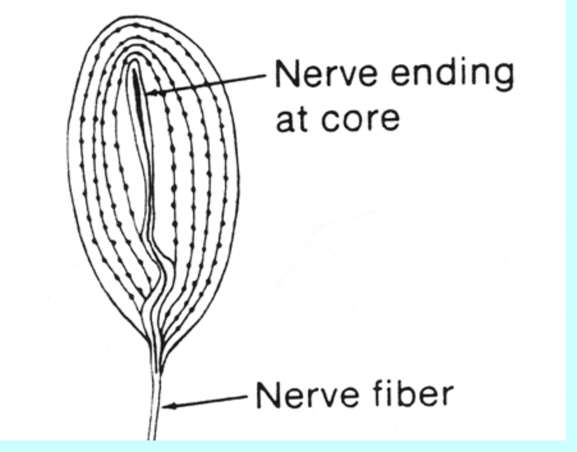
Touch



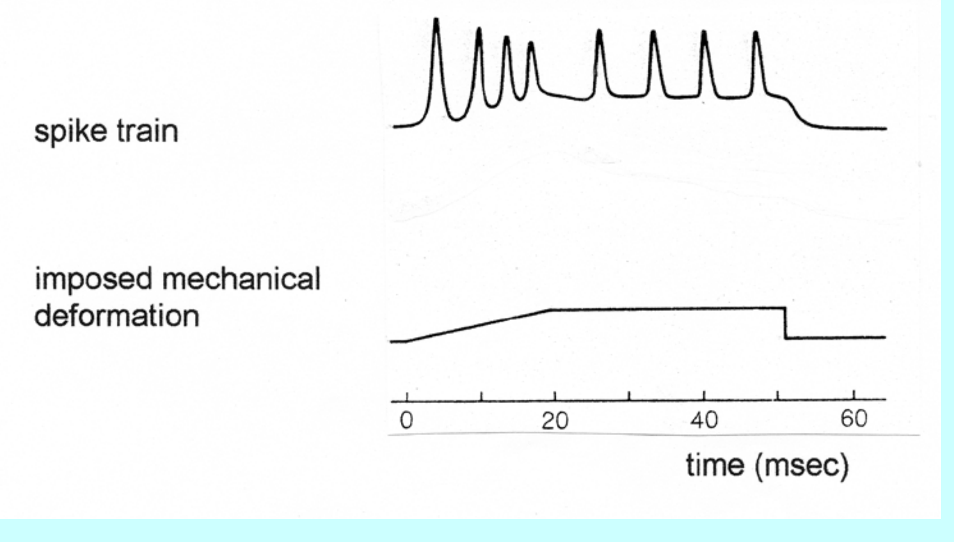
Several receptors contribute to touch sensation, the contribution of each depending on its transduction properties and it location. Location is important both in terms of skin layer (the different layers posses different mechanical properties) and the depth from the surface (stress intensity).

Touch

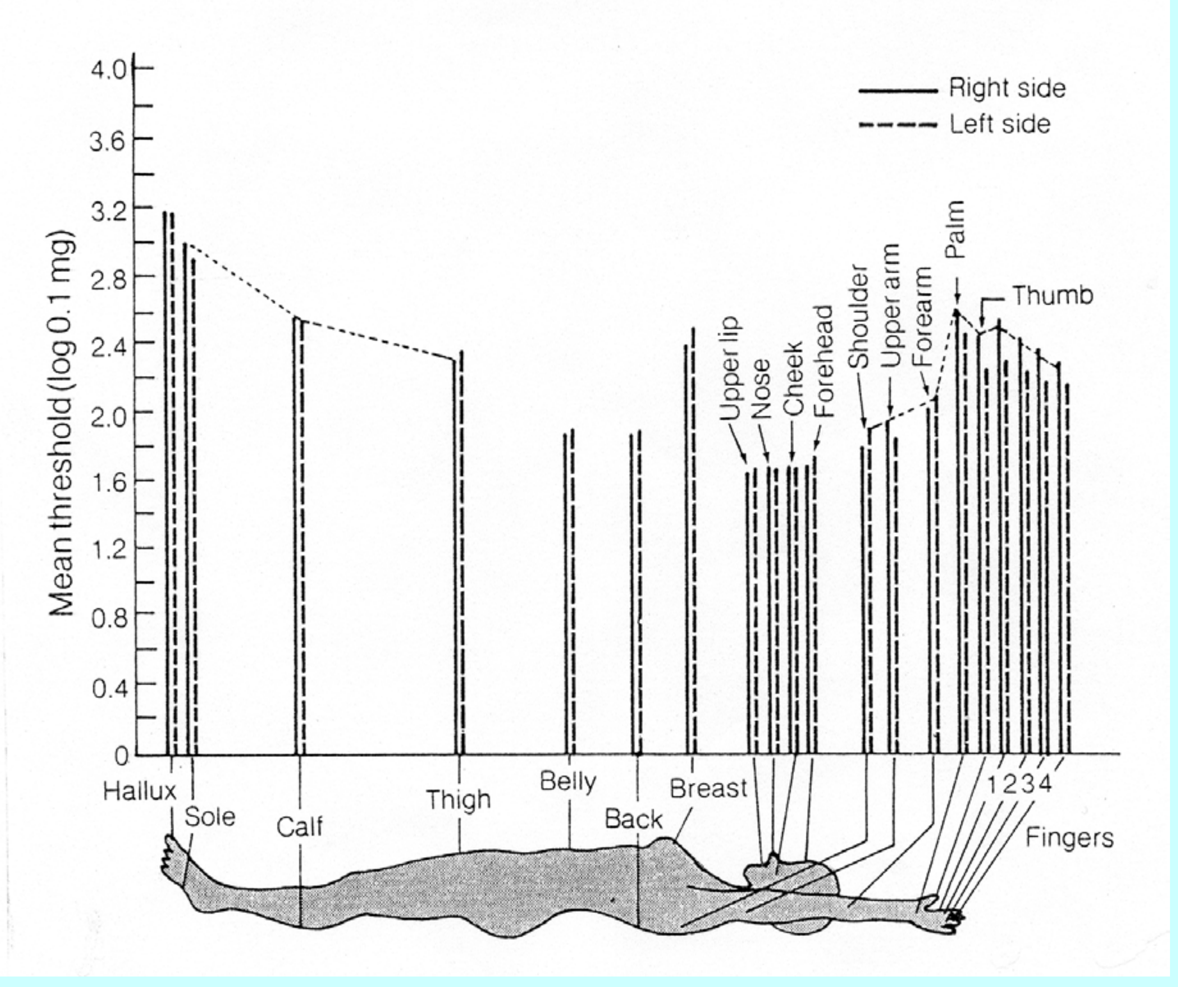
The pacinian corpuscle is typical of the receptors which produce touch sensation. It consist of a neuron axon surrounded by concentric layers of tissue.



The example below presents the mechanical deformation applied to a pacinian corpuscle and the train of electro-chemical spikes transmitted to the brain. The properties of the mechanical stimulus are encoded in terms of both spike amplitude and spike frequency in a complex nonlinear manner.



Touch



Touch sensitivity is not uniform across the body. It changes as a function of the number and type of receptors present locally. The graph below presents the perception threshold for various body locations measured with a small medical indentor needle.

Touch

Touch receptors have been found to be frequency selective in their response.

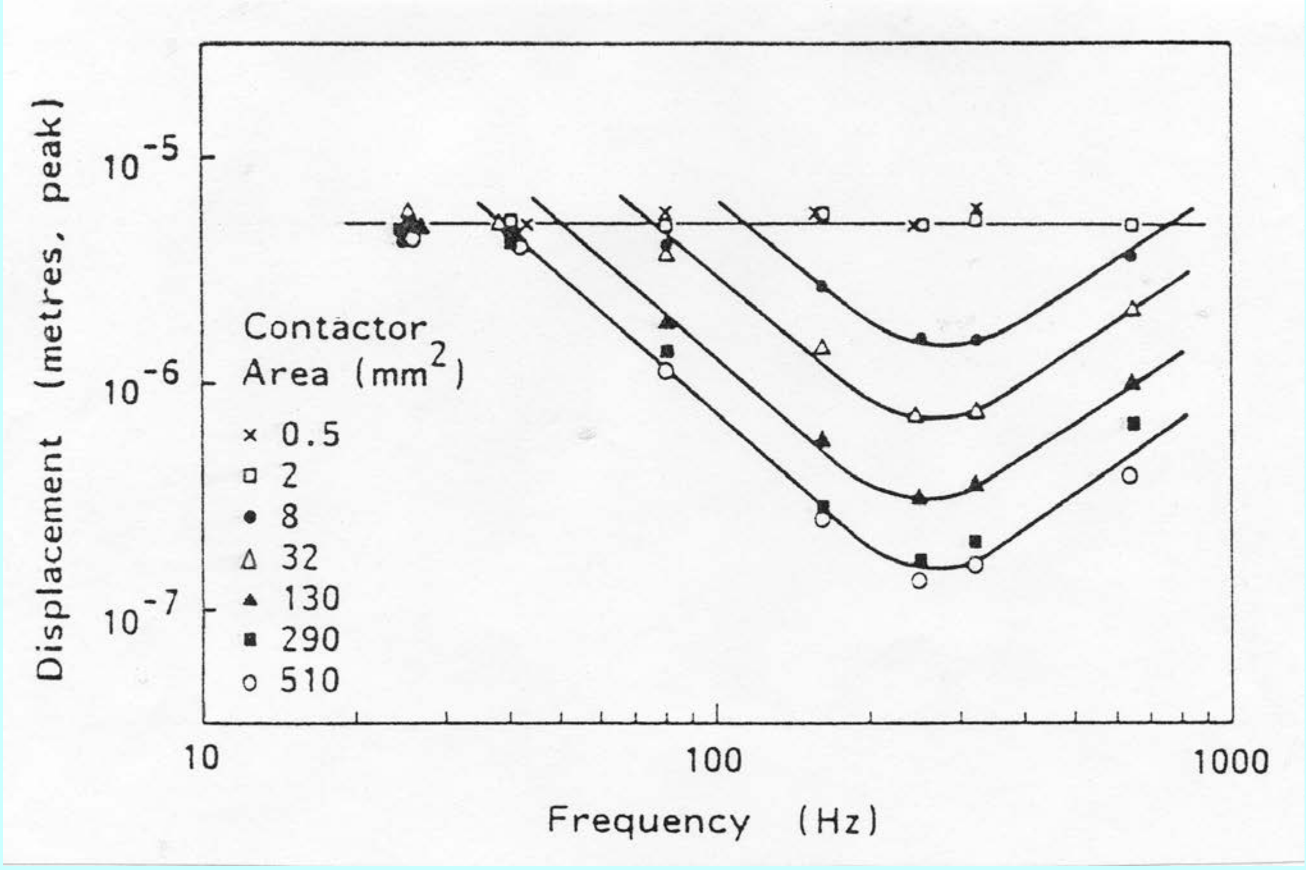
Merkel and Ruffini receptors are responsible for low frequency sensation such as static pressure and quasi static changes in the pressure.

Meissner and Pacini receptors contribute to the sensation of rapid changes such as when running the hand over a rough surface.

Touch

Receptor	Frequency Range
Ruffini corpuscle	< 1 Hz
Merkel receptor	5 - 15 Hz
Meissner corpuscle	20 – 50 Hz
Pacinian corpuscle	50 - 1000 Hz

Touch



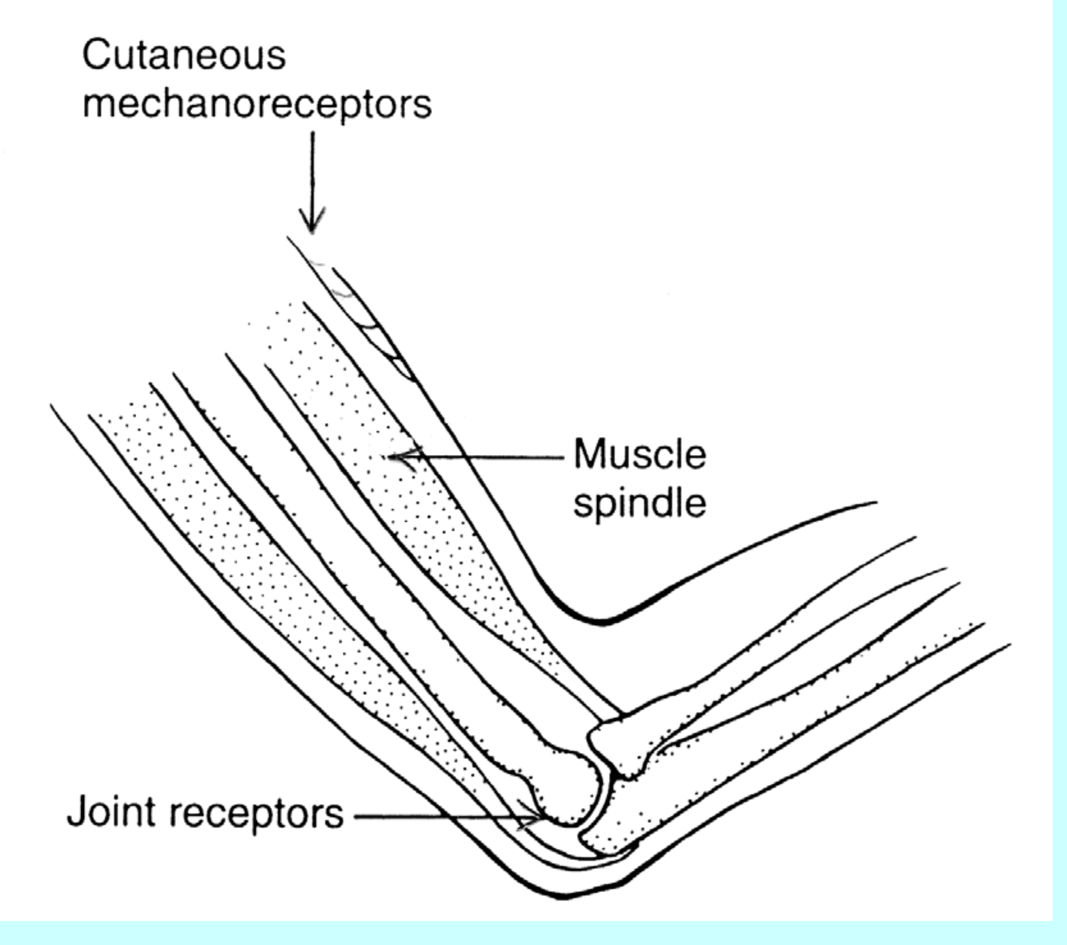
The graph presents perception thresholds from an experiment in which a vibrating indentor needle was pushed against the skin of the thumb with a constant force then vibrated with sinusoidal signals.

It can be seen that touch sensation is frequency dependent. This dependency starts, however, only after 40 Hz when the pacinian corpuscles provide a large contribution to the total sensation.

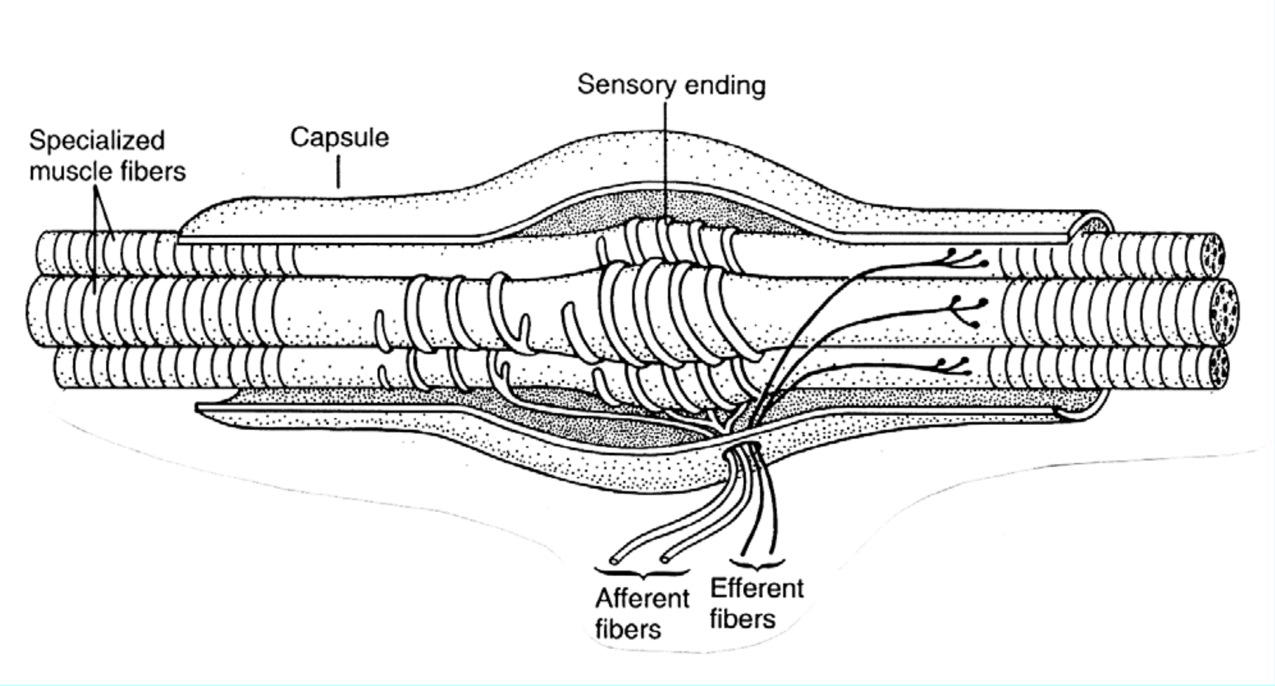
Proprioception

Proprioception is the sense which provides the nervous system with the information needed to track the position and velocity of the body segments, along with the muscle forces involved.

Three types of receptors contribute to the limb position sense: mechanoreceptors in the skin, mechanoreceptors in the joints and muscle spindle receptors.

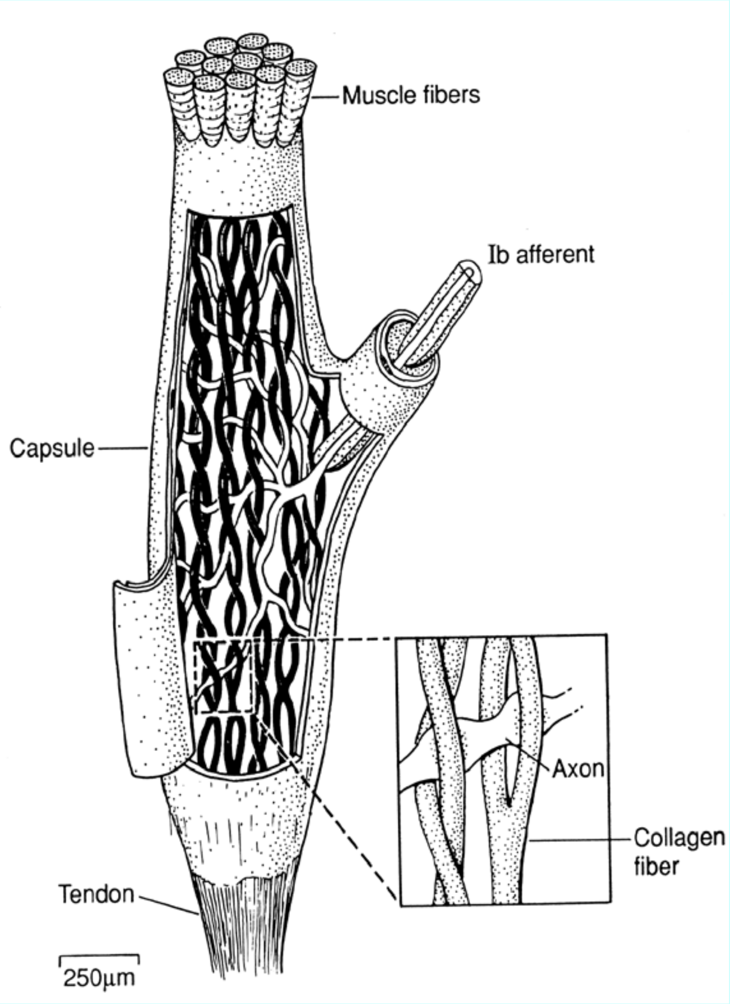


Proprioception



The muscle spindle is a specialised receptor which is located within muscle packs in parallel with the muscle fibres. The endings of special neurons are wrapped around muscle fibres. Changes in length of the muscle fibres produces electro-chemical signals which encode both the relative displacement and the relative velocity of the muscle fibres.

Proprioception



The golgi tendon organ is a special receptor located at the meeting point between muscle fibres and tendons. It is in series with the muscle fibres and consists of intertwined sensory neuron axons and collagen fibres. It produces an electro-chemical signal which is proportional to the force acting across it.

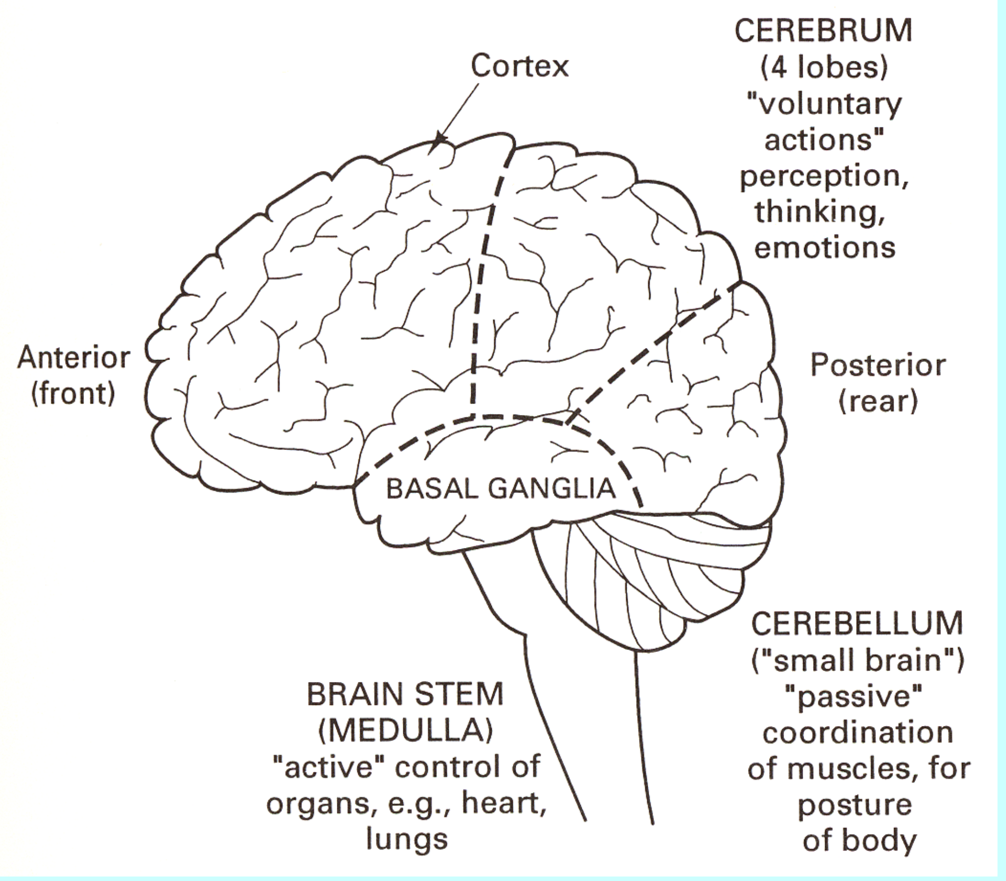
Proprioception

The frequency response characteristics of muscle spindles and golgi tendon organs are difficult to quantify for several reasons. For example, central control from efferent fibres strongly modulates the outputs of muscle spindles and can even cause a stop to receptor output altogether.

Measurements made by applying vibrations directly to muscle fibres and tendons have shown, however, that these receptors are capable of producing output for frequencies up to 300 Hz.

Since muscles are low pass systems which cannot move faster than 4 Hz, it would seem that the receptors serve a sensory role beyond the simple monitoring of muscle action.

The Brain



Cerebrum: processes sensory data, performs conscious thought and stores information.

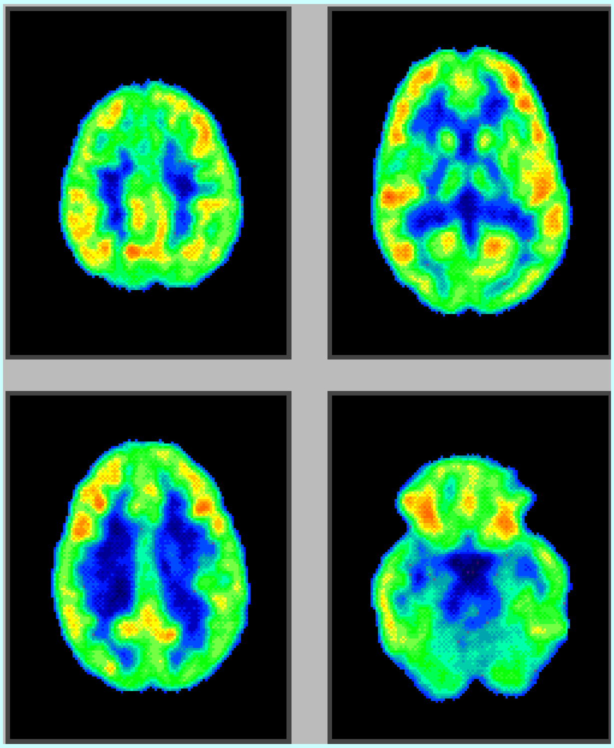
Cortex: interprets sensory input and controls voluntary movement.

Basal ganglia: controls semi-voluntary complex activities such as walking.

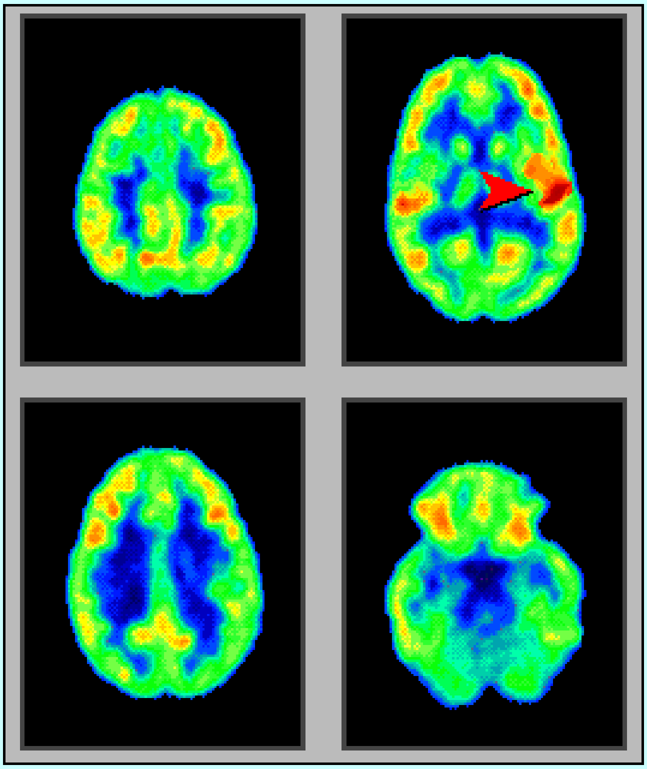
Cerebellum: integrates and distributes impulses from the cerebral centres to the motor neurons of the spinal cord.

Brain stem: crossover point for all signals coming and going from the brain. Controls sympathetic activities like heart rate, blood pressure, swallowing and breathing.

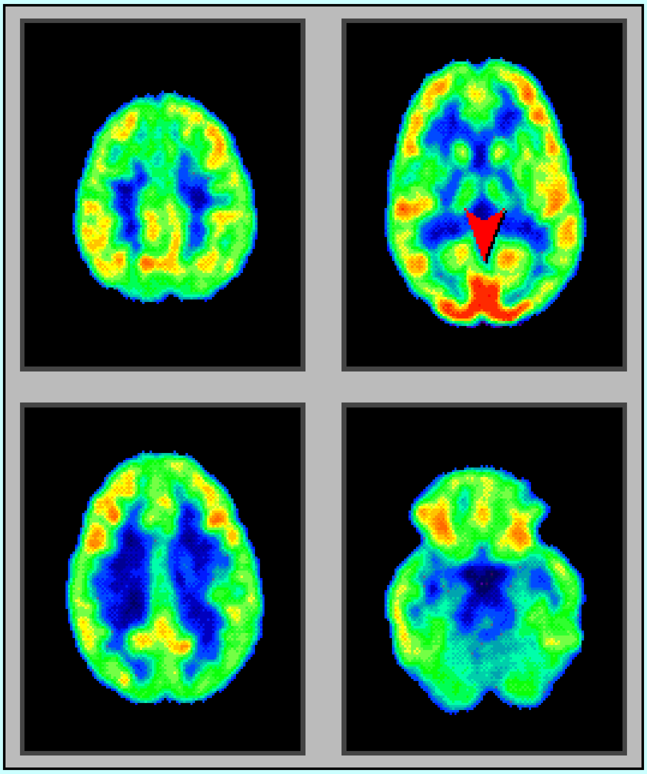
Brain Imaging



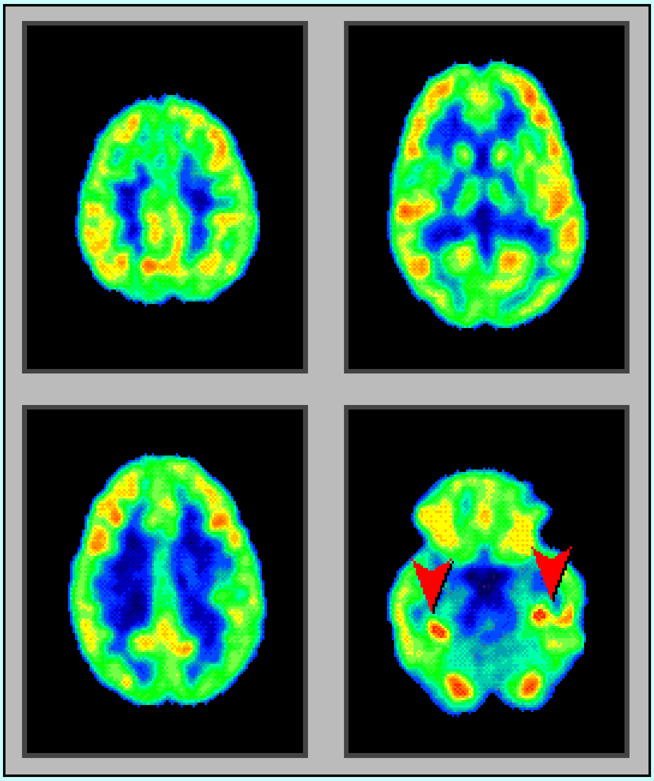
resting



listening to music

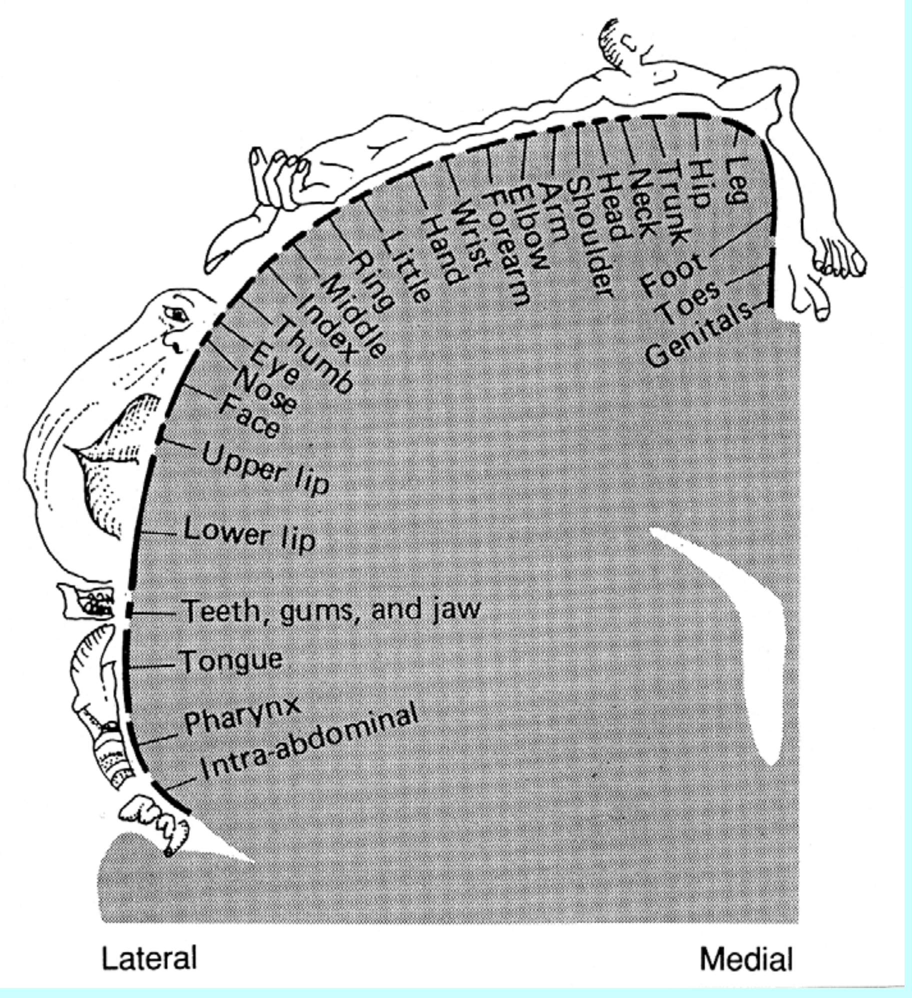


viewing an image



learning

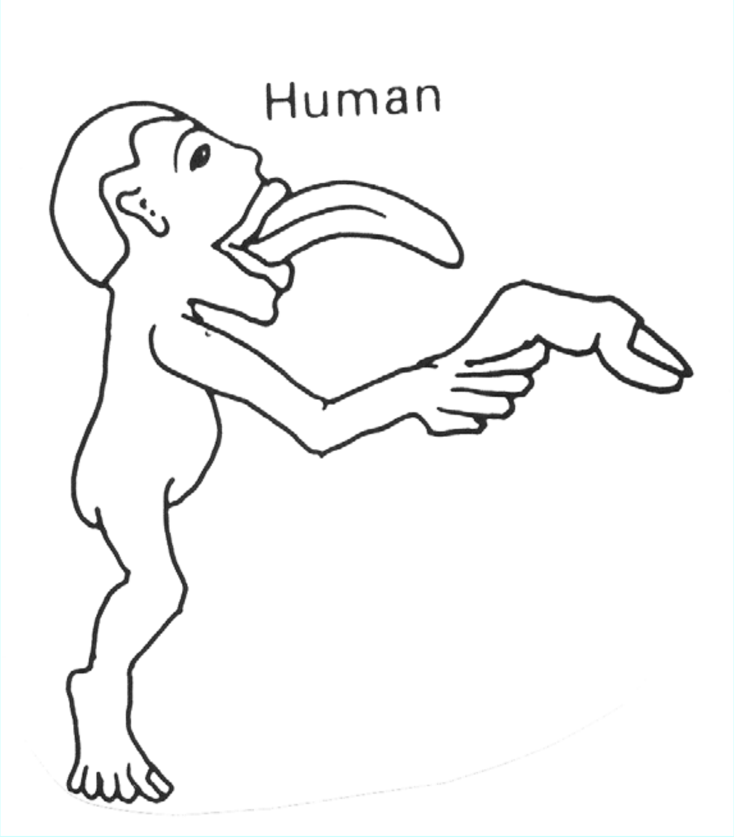
Somatosensory Cortex



Medical experimentation has shown that the area of the cerebral cortex is organised into a precise representation of the external surface of the body.

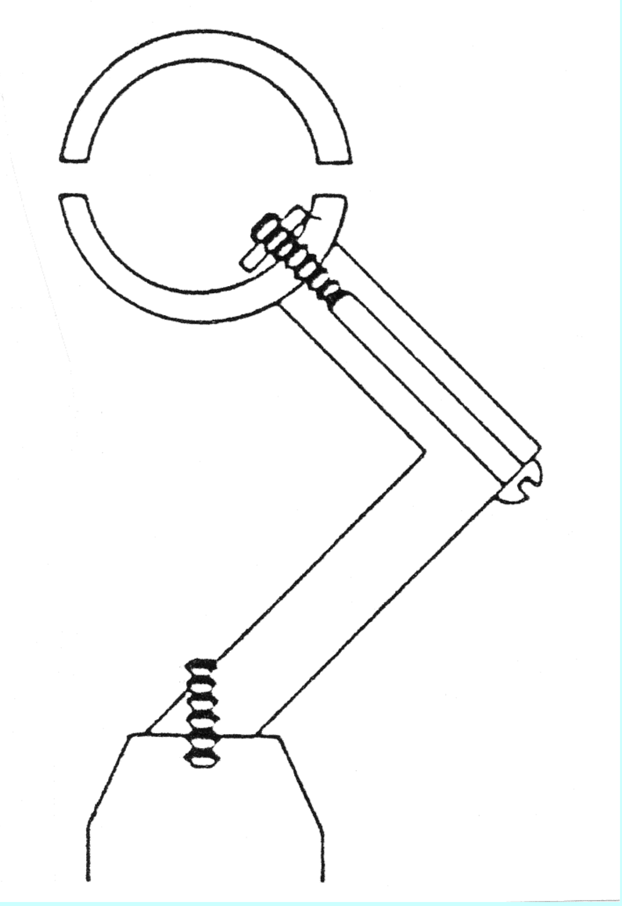
A somatosensory map called a homunculus is used to describe the cortical area dedicated to the processing of signals from each body region.

Somatosensory Cortex



An important conclusion that can be drawn from the sensory homunculi is that the nervous system dedicates greater processing power, and thus greater attention, to signals arriving from the face and hand.

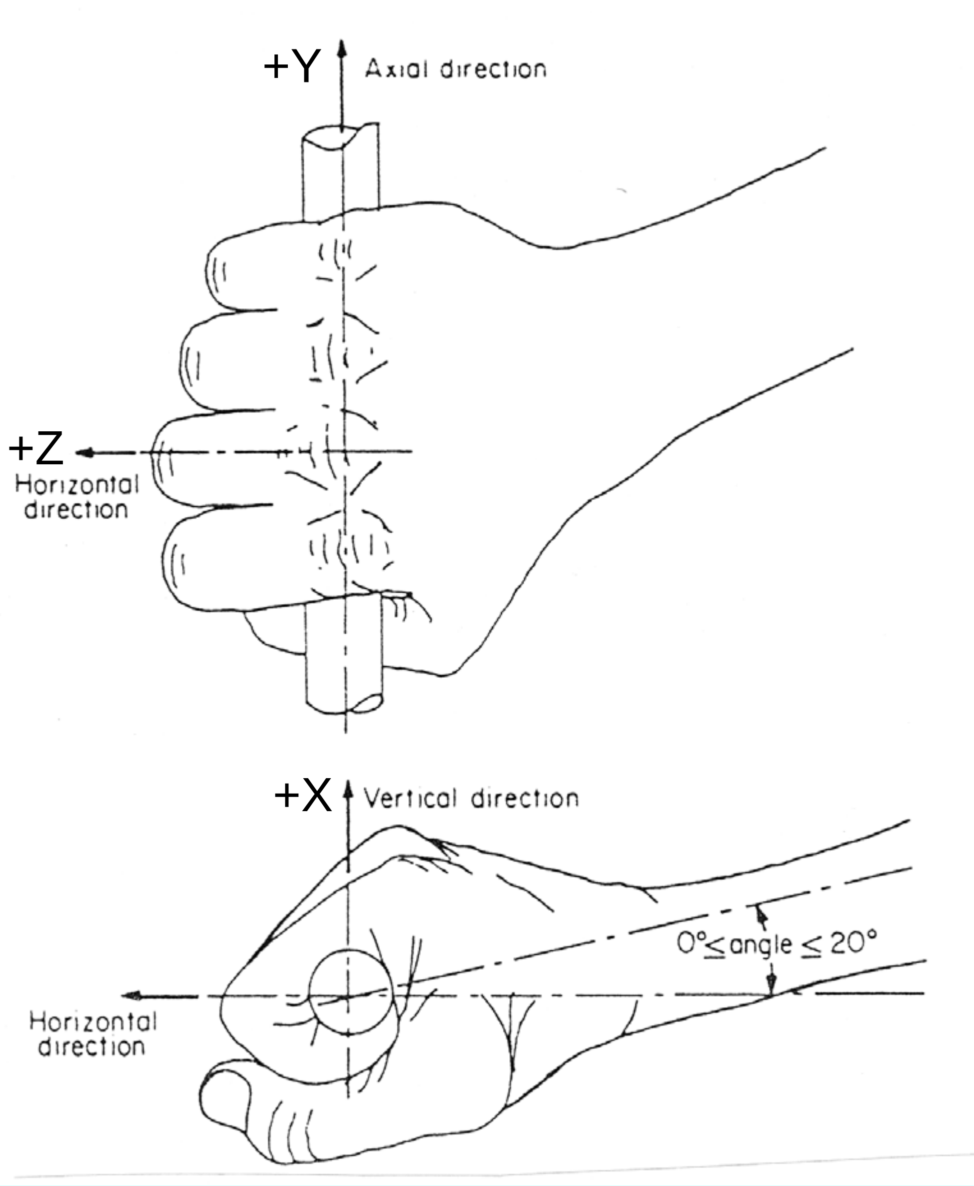
Hand-Arm Vibration



Studies have investigated the mechanical characteristics and the vibration perception properties of the human hand-arm system.

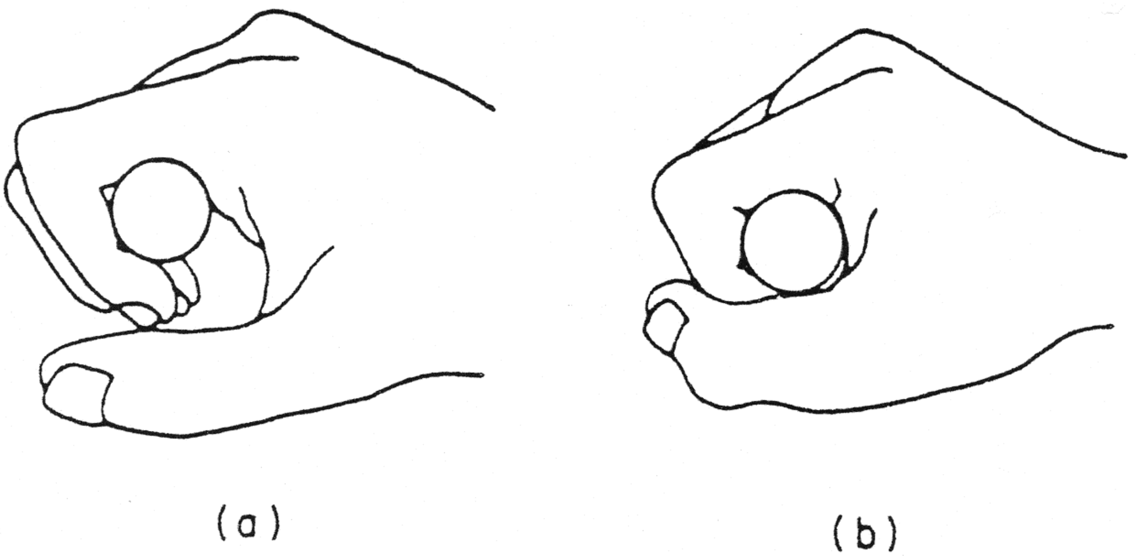
These studies used handles equipped with strain gauges to measure the grip force such as the one above used by Reynolds et. al.

Hand-Arm Vibration



Hand-arm vibration exposure is normally tested and reported with respect to the basicentric coordinate system defined by the orientation of the handle being gripped.

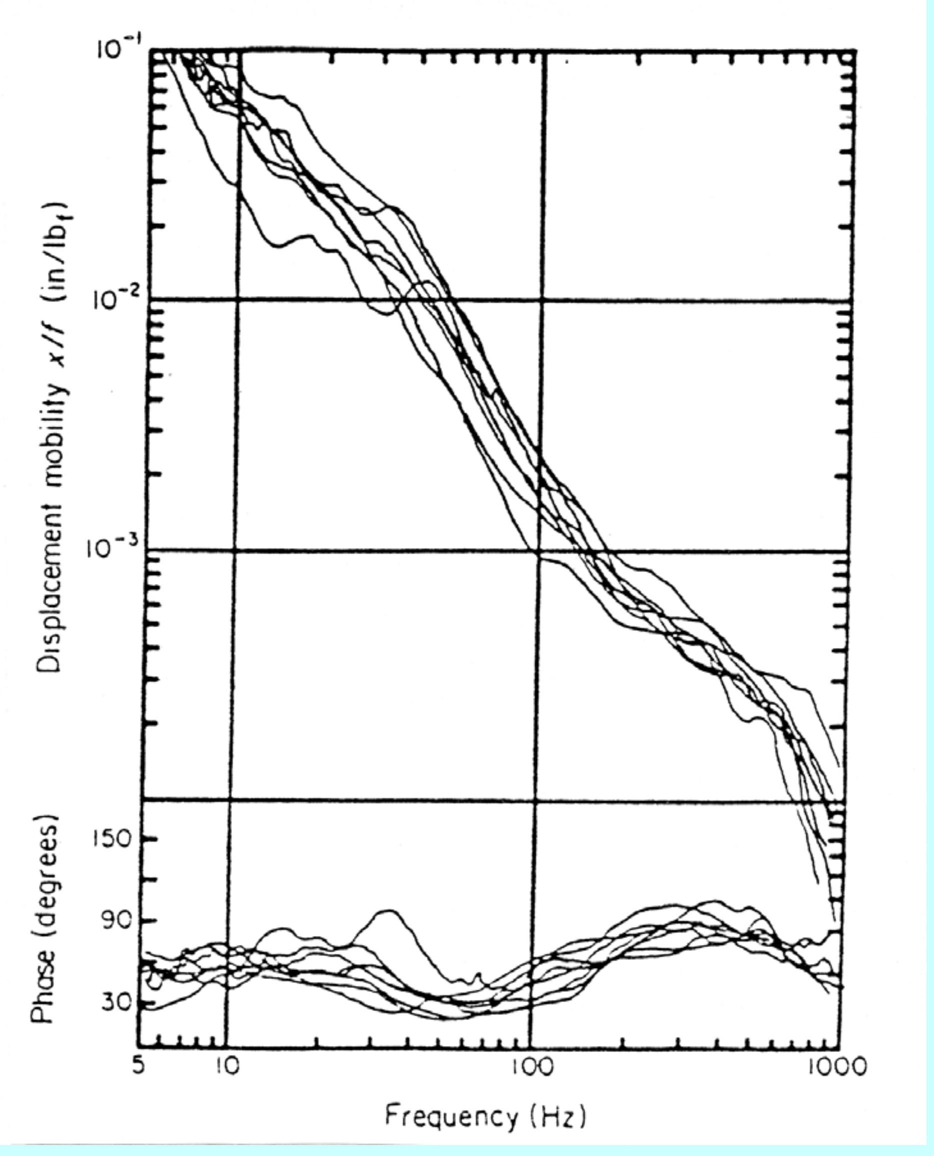
Hand-Arm Vibration



Types of grips. (a) Finger grip; (b) palm grip.

The mechanical and the perceptual response of the hand-arm system is affected by both the strength (coupling force) and the type of grip employed.

Hand-Arm Vibration



Reynold's et al. placed an accelerometer and a load cell at the interface between handle and vibration shaker so that the driving point mobility function (displacement/force) could be calculated.

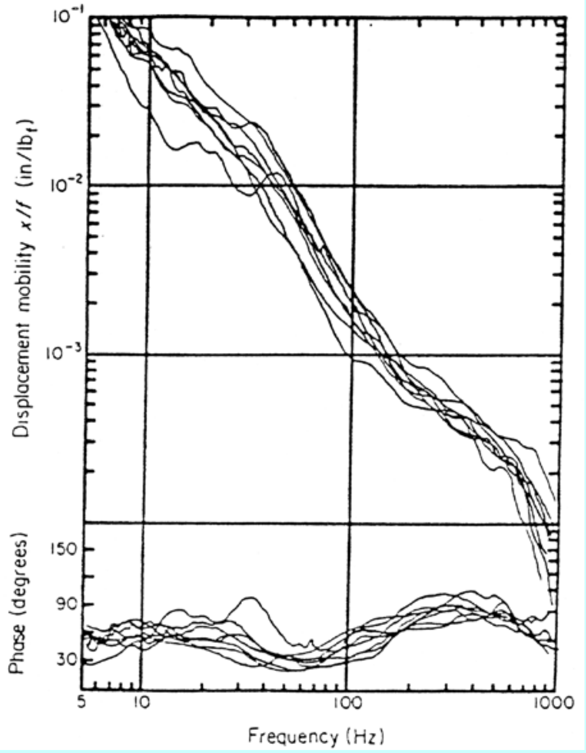
Curves from several subjects are presented above for the vertical direction and the 2 pound grip force. The absence of sharp resonance peaks shows that the hand and arm are highly damped.

Hand-Arm Vibration

A fundamental mechanical characteristic of the hand-arm system is the high level of damping. The tissues dissipate much of the vibrational energy to to which they are exposed. This can be seen by expressing the modulus of the dissipated energy $|E_d|$ in terms of the modulus of the driving point mobility function and the amplitude of the displacement input |X|

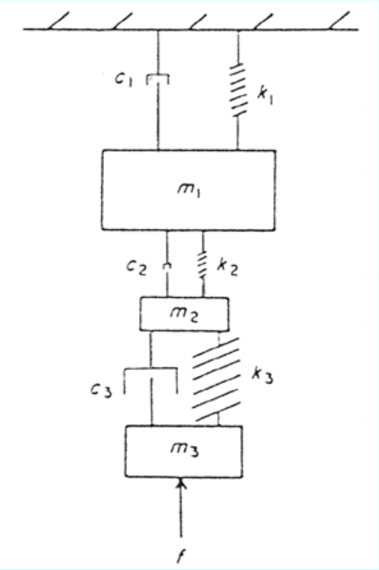
$$|E_d| = |X|^2 \,\mathrm{Im}\left[\frac{F}{X}\right] = |X|^2 \left[\frac{F}{X}\right] \sin\phi$$

Mobility functions for the hand-arm system have a modulus which decreases linearly with frequency and a phase angle which remains almost constant. Since the dissipated energy goes with the inverse of the mobility function, it can be seen that the dissipated energy increases linearly as a function of frequency.



Hand-Arm Vibration

Reynold's et al. fitted three degree of freedom spring-mass-damper models to their test data. They found that the parameters were functions of the direction of vibration, the grip force and the grip type.



Model coefficients for grip configurations in the vertical direction

	2 lb$_f$ Finger	8 lb$_f$ Finger	2 lb$_f$ Palm	8 lb$_f$ Palm	
m_1	1·420 × 10^{-1}	1·577 × 10^{-1}	1·805 × 10^{-1}	1·998 × 10^{-1}	kg
m_2	3·558 × 10^{-2}	4·820 × 10^{-2}	2·997 × 10^{-2}	2·997 × 10^{-2}	kg
m_3	7·887 × 10^{-2}	8·764 × 10^{-2}	9·990 × 10^{-2}	9·990 × 10^{-2}	kg
k_1	1·573 × 10^{4}	2·240 × 10^{4}	2·557 × 10^{4}	2·837 × 10^{4}	Newton/m
k_2	3·502 × 10^{1}	4·746 × 10^{1}	2·924 × 10^{1}	2·959 × 10^{1}	Newton/m
k_3	1·506 × 10^{5}	3·539 × 10^{5}	7·723 × 10^{4}	1·576 × 10^{5}	Newton/m
c_1	1·700 × 10^{2}	2·136 × 10^{2}	2·434 × 10^{2}	2·714 × 10^{2}	Newton-s/m
c_2	3·327 × 10^{0}	3·520 × 10^{0}	2·277 × 10^{0}	3·261 × 10^{0}	Newton-s/m
c_3	2·609 × 10^{2}	3·520 × 10^{2}	2·277 × 10^{2}	3·261 × 10^{2}	Newton-s/m

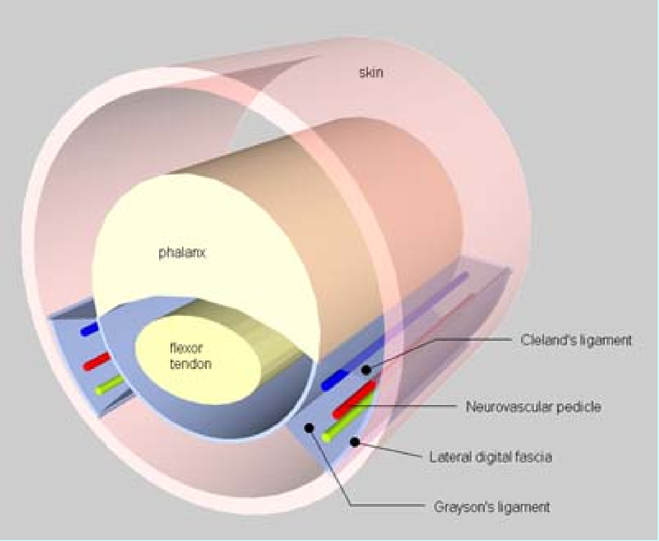
Model coefficients for grip configurations in the horizontal direction

	2 lb$_f$ Finger	8 lb$_f$ Finger	2 lb$_f$ Palm	8 lb$_f$ Palm	
m_1	1·136 × 10^{-1}	1·504 × 10^{-1}	1·998 × 10^{-1}	1·998 × 10^{-1}	kg
m_2	2·524 × 10^{-2}	4·890 × 10^{-2}	4·995 × 10^{-2}	5·994 × 10^{-2}	kg
m_3	6·310 × 10^{-2}	7·519 × 10^{-2}	9·990 × 10^{-2}	9·990 × 10^{-2}	kg
k_1	1·009 × 10^{3}	4·010 × 10^{3}	2·014 × 10^{3}	5·324 × 10^{3}	Newton/m
k_2	1·219 × 10^{1}	1·235 × 10^{1}	1·261 × 10^{1}	1·513 × 10^{1}	Newton/m
k_3	1·555 × 10^{5}	3·634 × 10^{5}	2·462 × 10^{5}	4·828 × 10^{5}	Newton/m
c_1	3·205 × 10^{1}	9·807 × 10^{0}	2·609 × 10^{1}	2·609 × 10^{1}	Newton-s/m
c_2	2·224 × 10^{0}	1·179 × 10^{1}	4·273 × 10^{0}	8·423 × 10^{0}	Newton-s/m
c_3	2·574 × 10^{2}	2·312 × 10^{2}	2·977 × 10^{2}	3·502 × 10^{2}	Newton-s/m

Model coefficients for grip configurations in the axial direction

	2 lb$_f$ Finger	8 lb$_f$ Finger	2 lb$_f$ Palm	8 lb$_f$ Palm	
m_1	4·207 × 10^{-2}	4·908 × 10^{-2}	2·103 × 10^{-2}	4·908 × 10^{-2}	kg
m_2	1·893 × 10^{-3}	1·718 × 10^{-3}	8·413 × 10^{-4}	2·454 × 10^{-3}	kg
m_3	2·103 × 10^{-2}	2·454 × 10^{-2}	1·402 × 10^{-2}	2·454 × 10^{-2}	kg
k_1	4·150 × 10^{3}	3·100 × 10^{3}	8·301 × 10^{1}	7·740 × 10^{2}	Newton/m
k_2	7·460 × 10^{0}	9·754 × 10^{0}	3·310 × 10^{0}	6·777 × 10^{0}	Newton/m
k_3	8·301 × 10^{3}	1·394 × 10^{4}	1·786 × 10^{4}	2·469 × 10^{4}	Newton/m
c_1	3·958 × 10^{1}	2·956 × 10^{1}	3·958 × 10^{0}	1·856 × 10^{1}	Newton-s/m
c_2	2·382 × 10^{-1}	1·804 × 10^{-1}	3·170 × 10^{-1}	2·592 × 10^{-1}	Newton-s/m
c_3	6·602 × 10^{1}	8·878 × 10^{1}	5·078 × 10^{1}	7·390 × 10^{1}	Newton-s/m

Hand-Arm Vibration

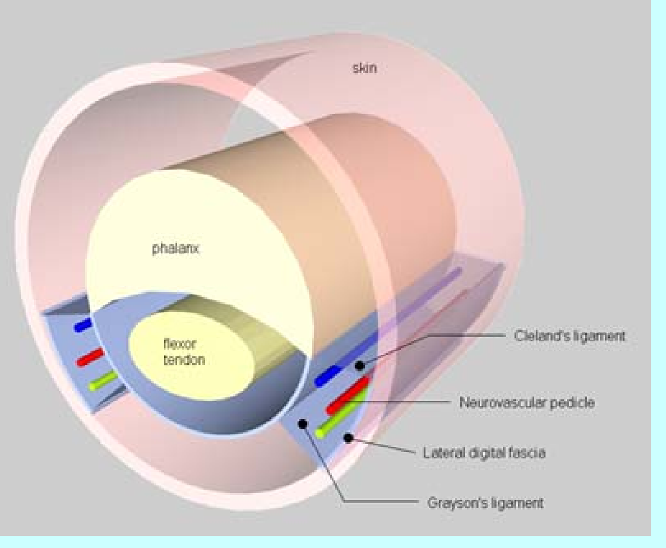


The outer tissue of the finger and hand is dermis and epidermis which consists of densely packed cells.

Below is the subcutaneous tissue which is of low density due to the presence of nerves, blood vessels and fluids.

Below this is a region of strong, dense, muscle tissue then bone.

Hand-Arm Vibration



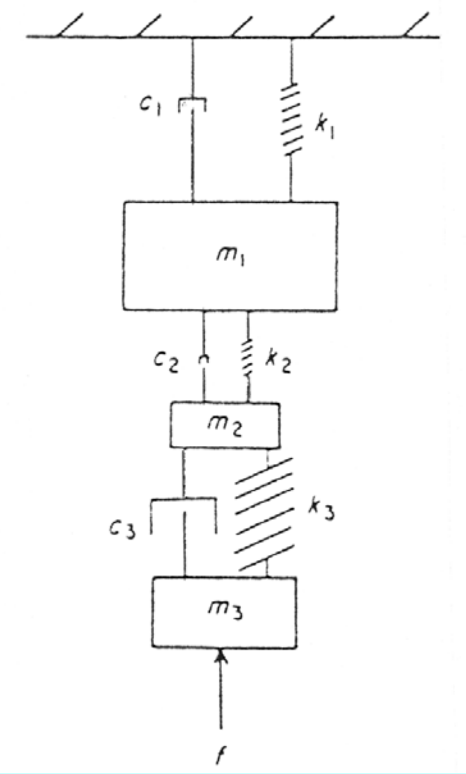
The bond between the dermis/epidermis layer and the subcutaneous layer is fairly strong.

The bond between the subcutaneous layer and the muscle layer is, instead, weak.

Hand-Arm Vibration

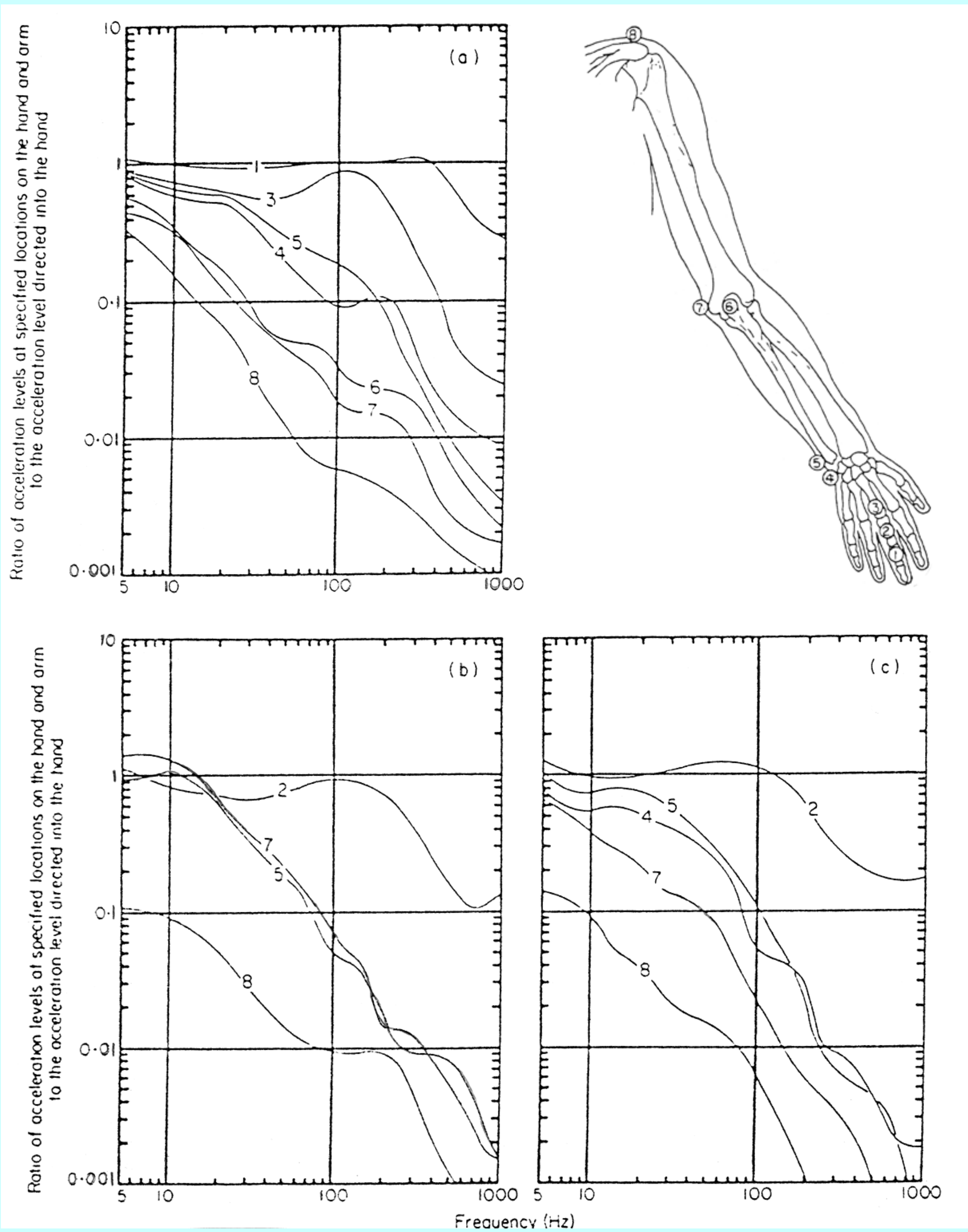
Comparison of the anatomy of the finger and hand to the identified mechanical models lead Reynolds to suggest the following interpretation.

m3	→	dermis and epidermis
m2	→	subcutaneous tissue
m1	→	muscle tissue
ground	→	bone (skeletal system)
k3,c3	→	strong coupling between the dermis/epidermis and subcutaneous layer
k2,c2	→	weak coupling between the subcutaneous layer and muscle layer
k1,c1	→	coupling between the muscle tissue and bone



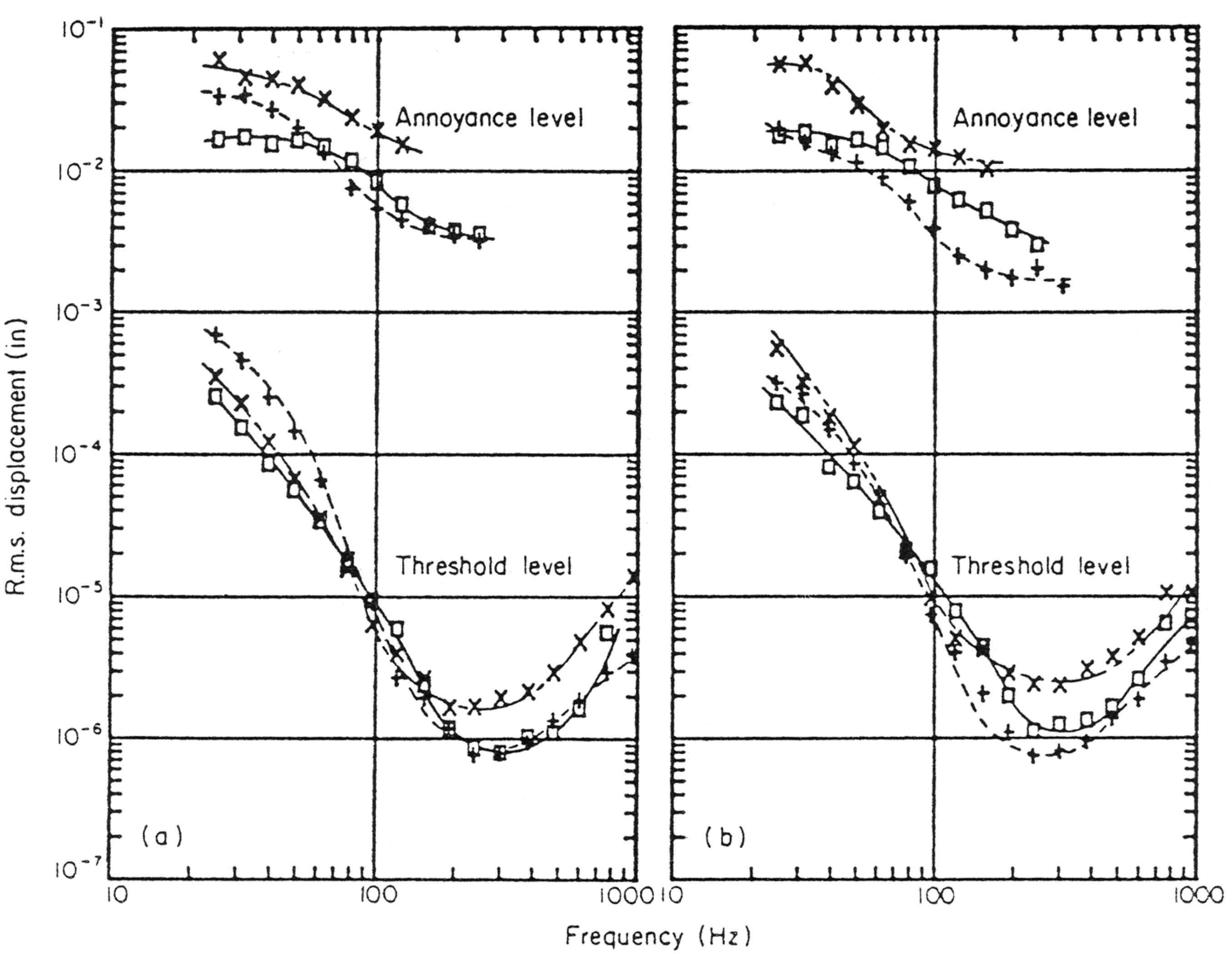
Hand-Arm Vibration

Studies have measured the acceleration transmissibility from vibrating handles to points on the hand and arm using lightweight accelerometers. The transmissibility curves below are for the vertical (a), horizontal (b) and axial (c) directions for one individual. **It is important to note that little vibration actually reaches the shoulder from the vibrating handle.**



Perception of Hand-Arm Vibration

The study by Reynolds et al. also produced perception threshold and annoyance level equal sensation curves which are shown below for the vertical (+), horizontal (□) and axial (x) directions for the 2 and an 8 pound palm grips. It is important to note that the threshold level curves closely follow the vibrotactile perception curves for human skin.

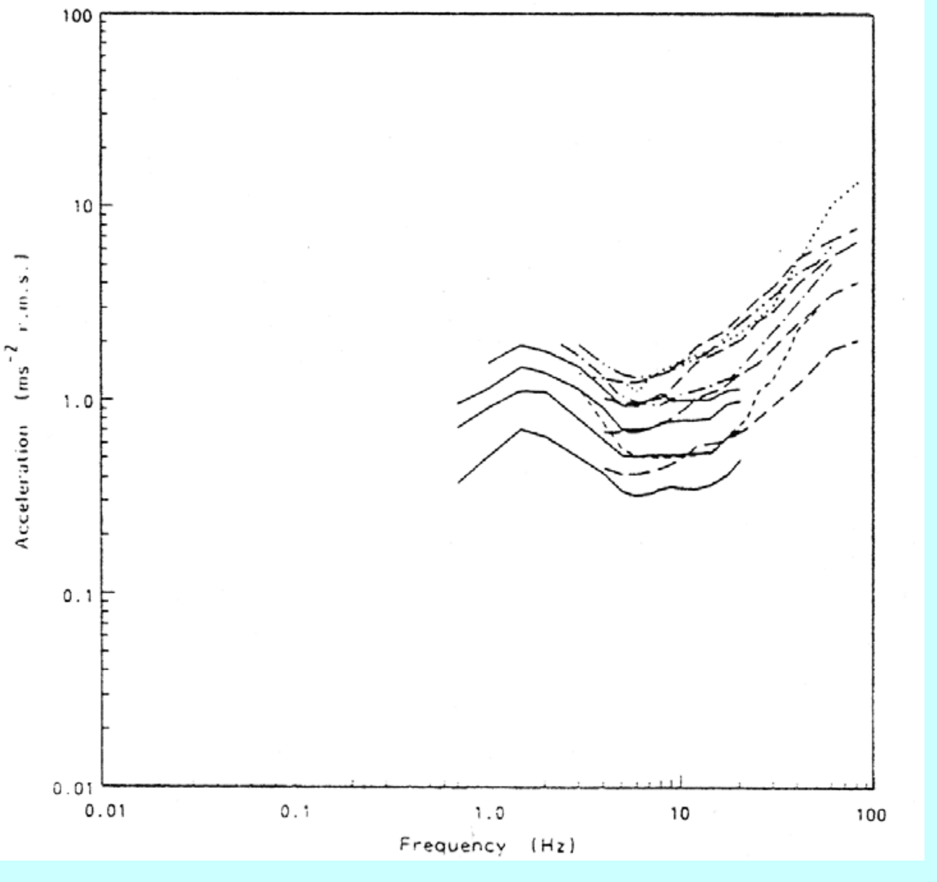


Perception of Hand-Arm Vibration

Several studies have measured the human perception of hand-arm vibration by means of experimental tests.

Such tests start by exposing the subject to a reference sinusoidal vibration of fixed frequency, amplitude and time duration. The vibration is then switched to a different frequency and the person is asked to adjust the amplitude until they feel the new signal is as close as possible to the original reference.

By testing many frequencies, many amplitudes and many people it is possible to define equal comfort (equal sensation) curves such as those shown below.

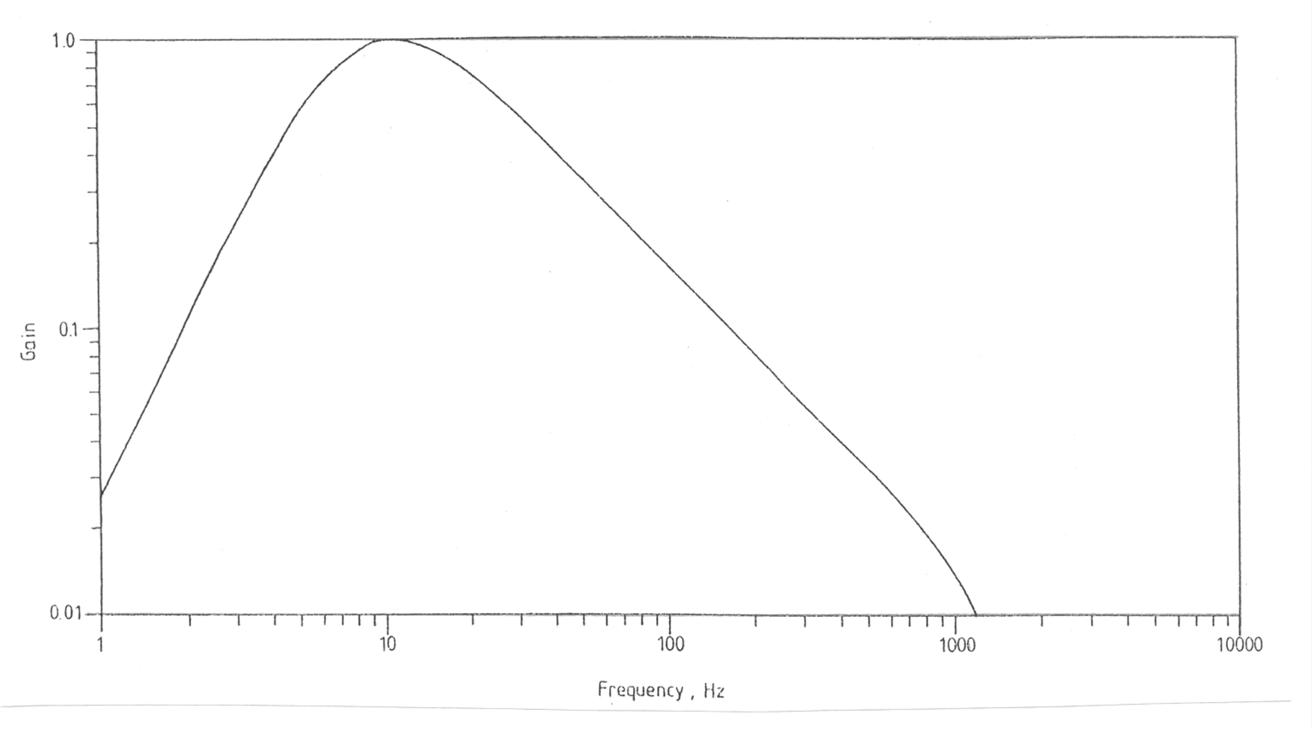


Perception of Hand-Arm Vibration

Equal Comfort Curves provide a means of quantifying the relative importance of the different frequencies present in vibration signals.

By taking the inverse of an equal comfort curve, and by dividing the result by the maximum value so as to normalise it, a **Frequency Weighting Curve** is obtained.

Perception of Hand-Arm Vibration



British Standard 6842 provides guidelines for the measurement and reporting of hand-arm vibration exposures. It defines a frequency weighting curve W_h for use along all three (x, y, and z) measurement axis.

Perception of Hand-Arm Vibration

Frequency weighting curves are used to represent human perception of vibration. They convert measured acceleration signals into perceived acceleration signals.

Perception of Hand-Arm Vibration

Hand-arm vibration standards now suggest the use of triaxial measurements in all cases where there is not clearly one dominant axis of vibration of the machine. The W_h weighting is applied to the acceleration signals of all three (x, y, and z) axis and the vector sum is determined.

$$a_{hv} = \sqrt{a_{hx}^2 + a_{hy}^2 + a_{hz}^2}$$

Perception of Hand-Arm Vibration

The frequency weighting filters convert acceleration signals into perceived acceleration signals. It still remains to quantify the complete disturbance. The statistical indices normally specified in the human vibration standards and literature are the following:

Root Mean Square Value

$$r.m.s. = \left[\frac{1}{T} \int_0^T a^2(t)\,dt \right]^{\frac{1}{2}}$$

Root Mean quad Value

$$r.m.q. = \left[\frac{1}{T} \int_0^T a^4(t)\,dt \right]^{\frac{1}{4}}$$

Vibration Dose Value

$$VDV = \left[\int_0^T a^4(t)\,dt \right]^{\frac{1}{4}}$$

Crest Factor

$$Crest\ Factor = \frac{peak\ value}{r.m.s.}$$

Perception of Vibration

People's feelings of discomfort involve more than the physiological intensity quantified by the frequency weightings.

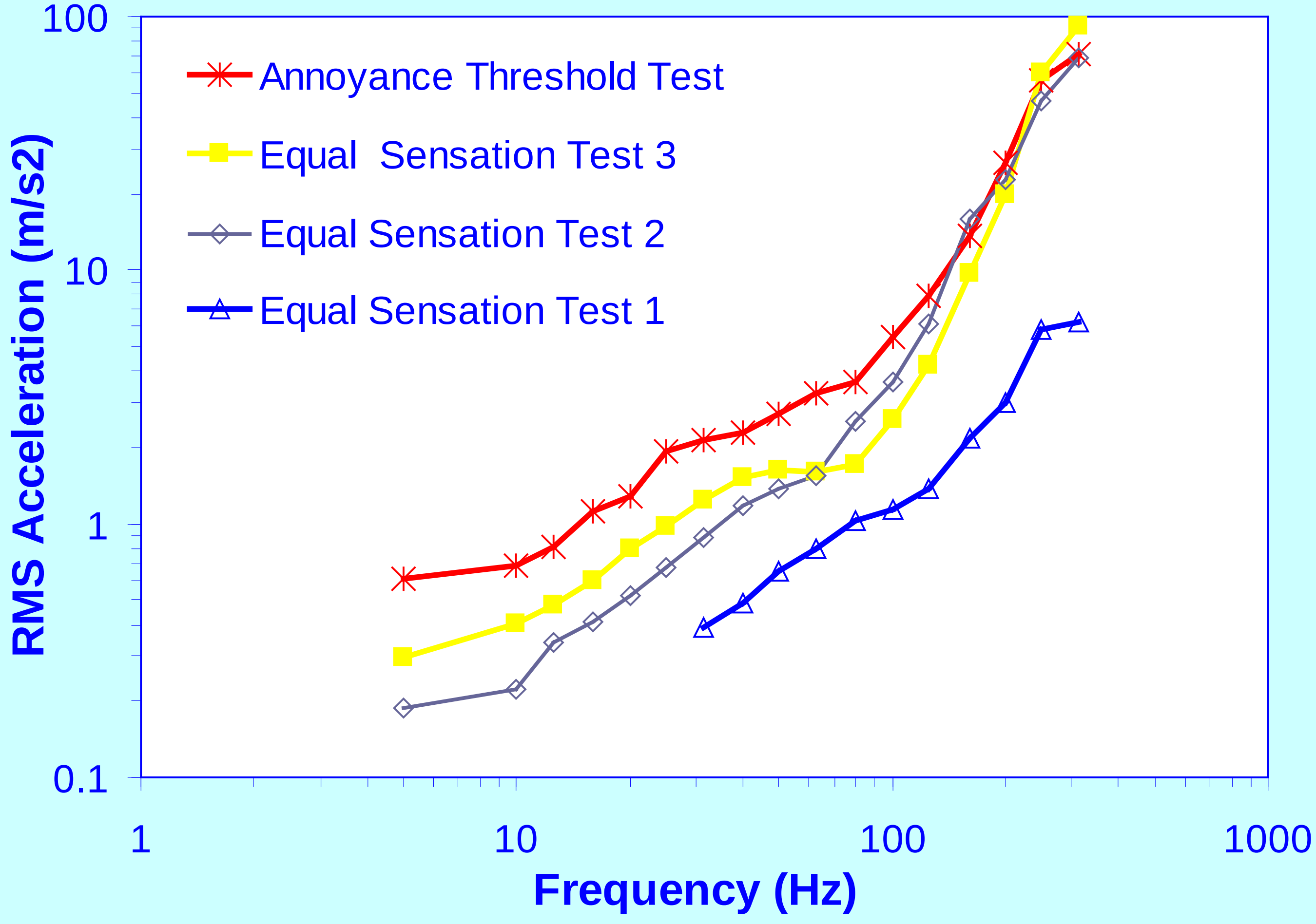
People's opinions also depend on cognitive elements such as the nature of the environment in which the vibration occurs, the expectations of the person involved, the role of the vibration in the person-machine relationship, the person's motivation, etc..

Steering Wheel Rotational Vibration

Studies by Giacomin and Shayaa have developed a frequency weighting curve for the rotational vibration of steering wheels. A bench was used which reproduced the sitting posture of drivers.

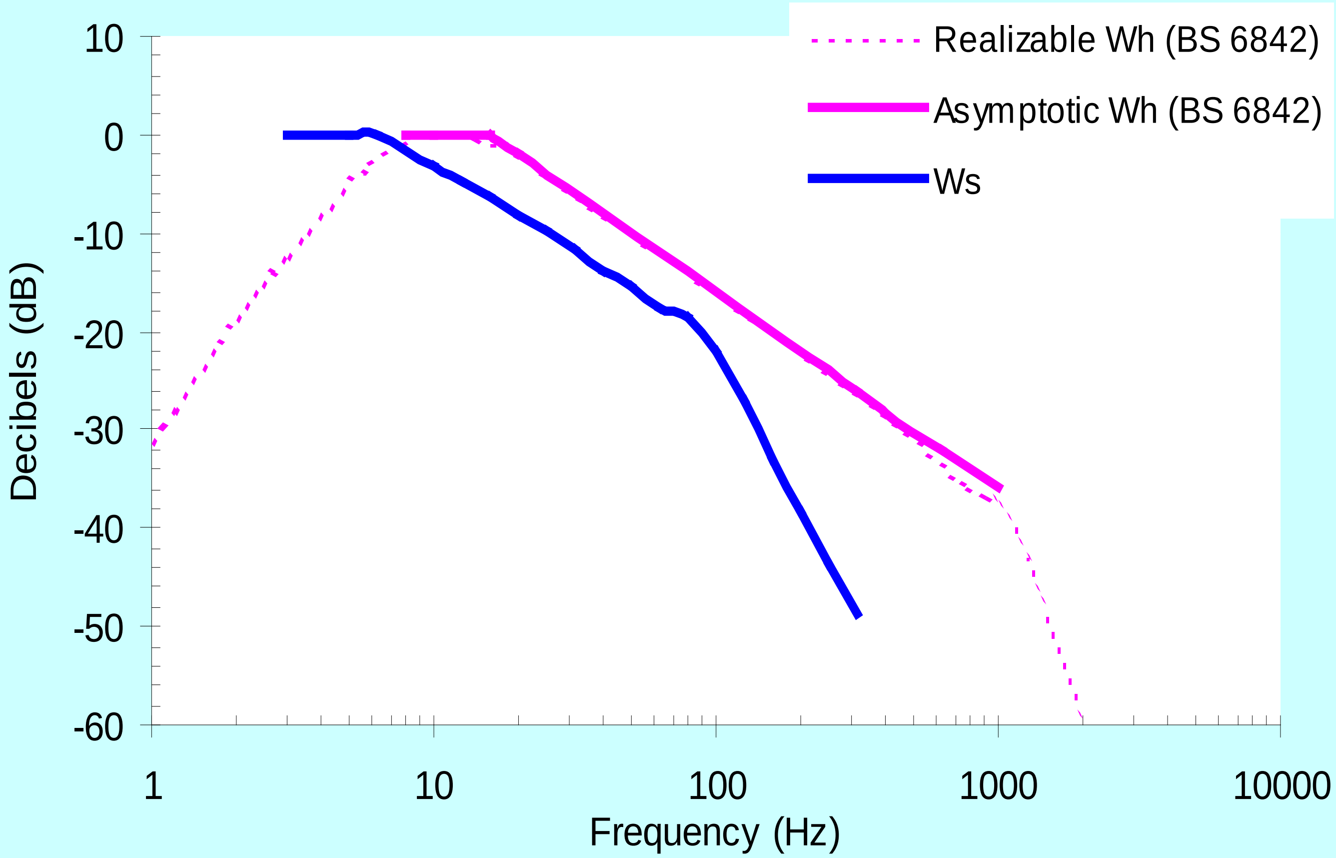
Geometric Parameter	Value
Steering column angle with respect to floor	23°
Steering wheel hub center height above floor	710 mm
Seat H point height from floor	275 mm
Horizontal distance from H point to steering wheel hub center	390–550 mm
Steering wheel handle diameter	12.5 mm
Steering wheel diameter	325 mm

Steering Wheel Rotational Vibration



Equal sensation and annoyance threshold curves were obtained for a group of 30 test subjects

Steering Wheel Rotational Vibration



Below 6.3 Hz the slope of W_s was defined as 0 dB per octave based on the current and Miwa's results.

From 6.3 to 63 Hz the slope of the mean contour was found to be -5.5 dB per octave, which for simplicity was rounded to -6 dB per octave in W_s.

From 63 to 315 Hz the slope of the mean contour was -16.3 dB per octave, which was rounded to -16 dB per octave in W_s.

Vibration White Finger

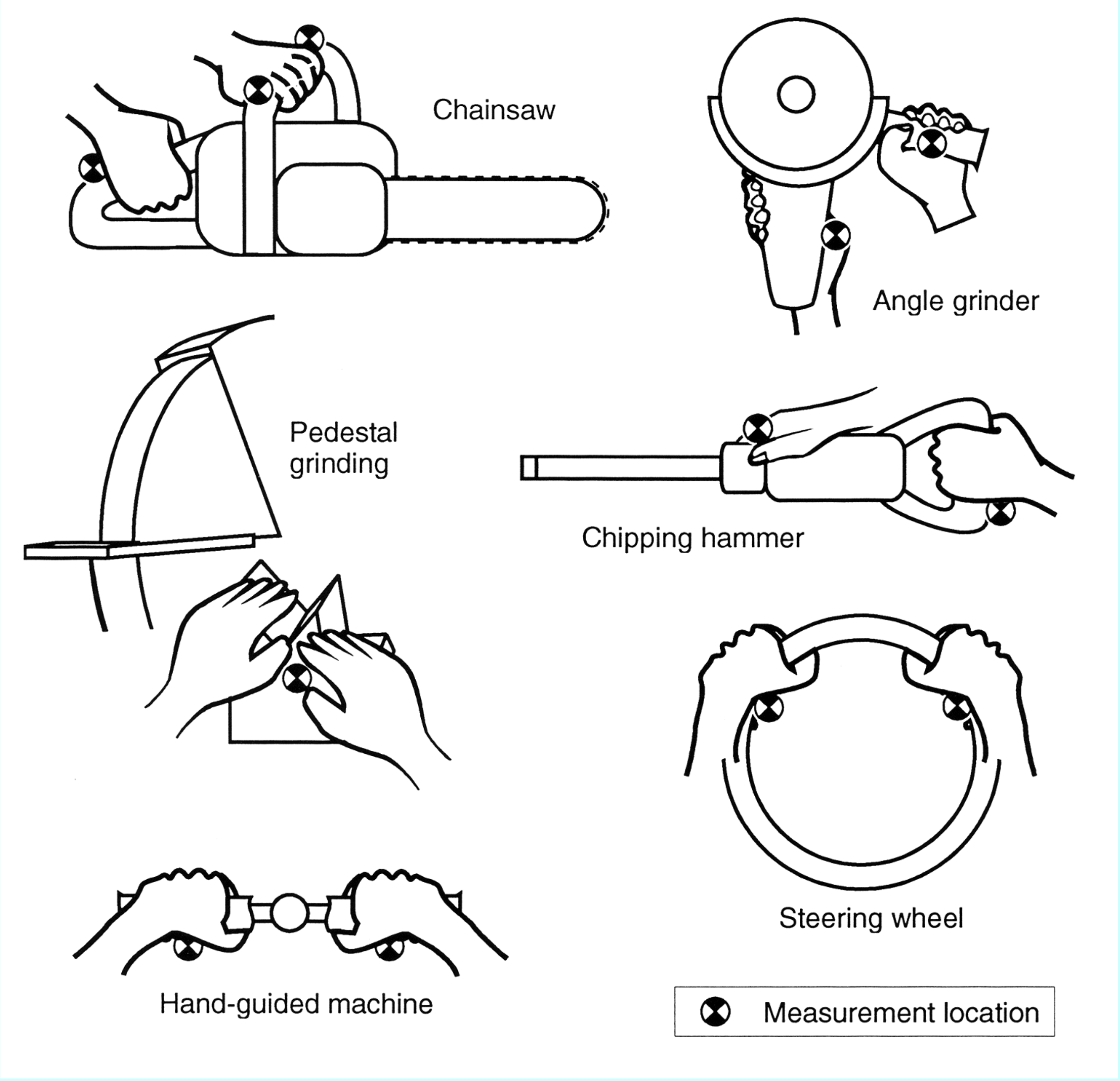
An important application of hand-arm measurements is for evaluating the tissue damage potential of a vibration exposure.

The name of the medical condition is Vibration Induced White Finger (VWF), also called Raynaud's Syndrome.

It is characterised by reduced blood circulation in the extremities of the fingers leading to tingling, numbness and blanching. Attacks are triggered by exposure to vibration, or cold, or a combination of the two.

Vibration White Finger

Examples of tools which can cause vibration white finger and which are thus routinely measured as part of health and safety evaluations include those shown below.



Vibration White Finger

BS6842 provides a table for estimating the vibration amplitudes and durations which would be expected to produce vibration white finger in people.

Table 5. Frequency weighted vibration acceleration magnitudes ($m \cdot s^{-2}$ r.m.s.) which may be expected to produce finger blanching in 10 % of persons exposed

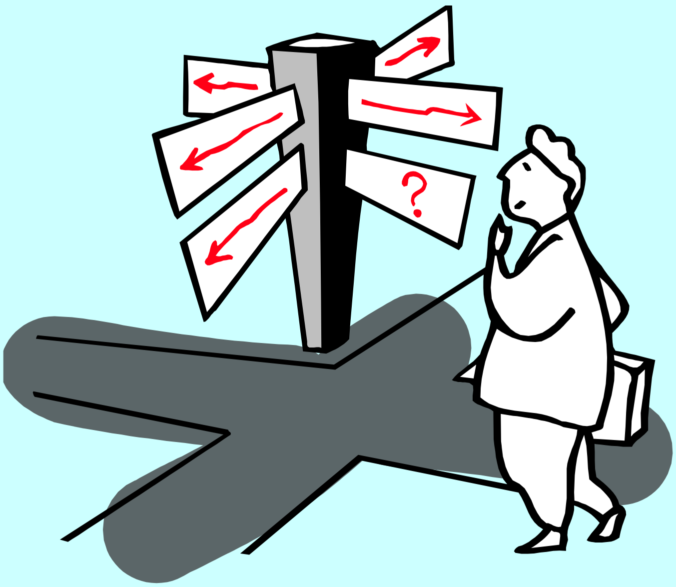
Daily exposure	Life-time exposure					
	6 months	1 year	2 years	4 years	8 years	16 years
8 h	44.8	22.4	11.2	5.6	2.8	1.4
4 h	64.0	32.0	16.0	8.0	4.0	2.0
2 h	89.6	44.8	22.4	11.2	5.6	2.8
1 h	128.0	64.0	32.0	16.0	8.0	4.0
30 min	179.2	89.6	44.8	22.4	11.2	5.6
15 min	256.0	128.0	64.0	32.0	16.0	8.0

NOTE 1. With short duration exposures the magnitudes are high and vascular disorders may not be the first adverse symptom to develop.

NOTE 2. The numbers in the table are calculated and the figures behind the decimal points do not imply an accuracy which can be obtained in actual measurements.

NOTE 3. Within the 10 % of exposed persons who develop finger blanching, there may be a variation in the severity of symptoms.

The Future



According to Brian Shackel (1991) Ergonomics and Human Factors have developed in stages:

1950s → Military ergonomics

1960s → Industrial ergonomics

1970s → Consumer products ergonomics

1980s → Human-computer interaction and software ergonomics

1990s → Cognitive ergonomics and organizational ergonomics

What will 2000-2010 come to be called ?

Universal Usability

In their 2000 paper "*User Sensitive Inclusive Design*" Newlell and Gregor suggest a new design paradigm called "Universal Usability" in which technological systems are developed for everyone, including people with disabilities.

Eco-ergonomics

In his 1997 *Handbook of Human Factors and Ergonomics* Gavriel Salvendy wrote "I predict that in the years 2000-2010 we will see an interest in eco-ergonomics. This will analyze how ergonomics methodology can be used to reduce pollution, decrease fuel consumption, reduce crime, reduce the size of very large cities, and so forth."

Information Intelligibility

In their 1997 book *Human Factors Engineering in System Design,* Andre and Schopper claimed that automation had changed the role of humans from “system controller performing the push-pulls” to that of “system monitor who attempts to head off deviations”. Due to the complexity of new technology they foresee that “Human Factors engineers of the future will concentrate on the intelligibility of information”.


FUZZY ENGINEERING
BART KOSKO
fuzzy logic
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Matthew Friedman
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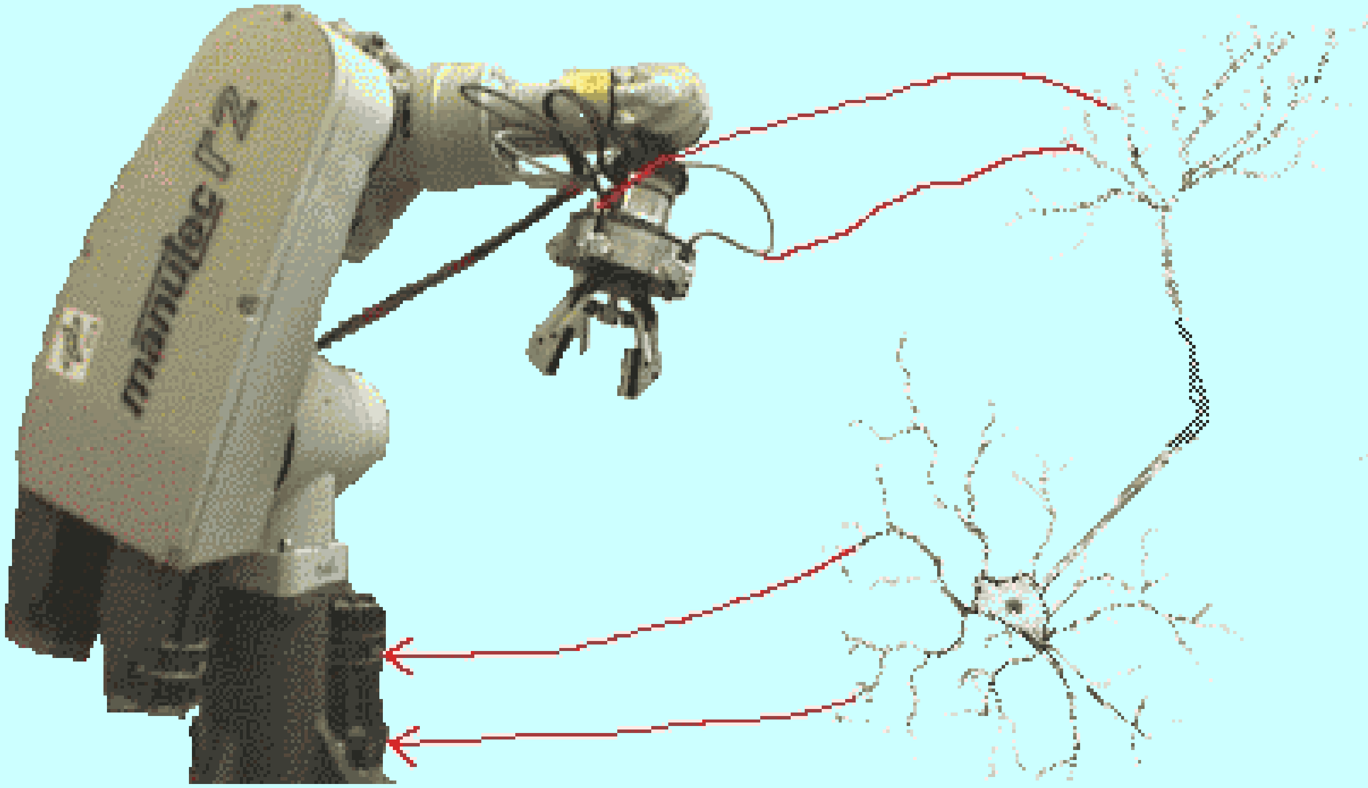
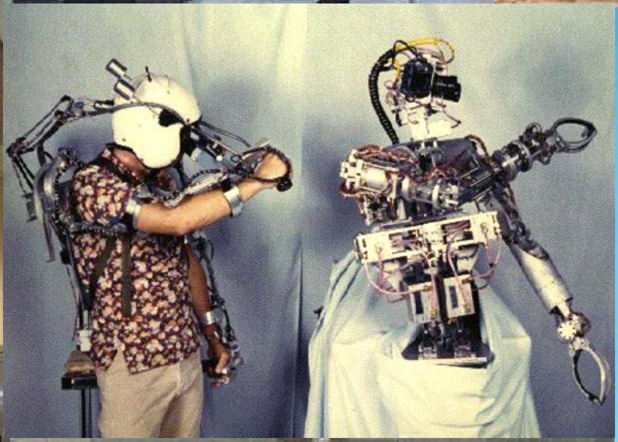
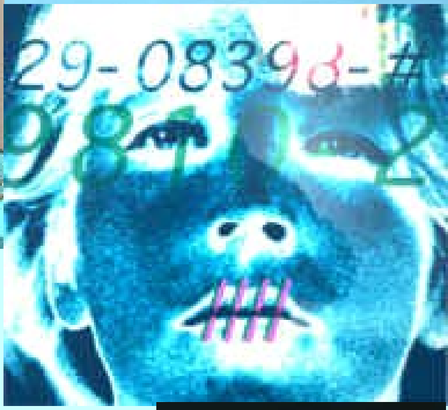


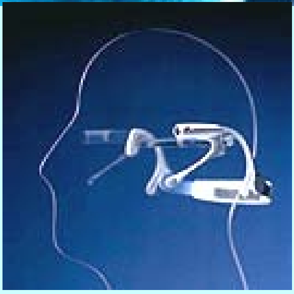
Man-Machine Integration

A paper by Giacomin and Abraham in 2000 briefly described a perception enhancement system for automotive steering. Applications such as the perception enhancement system are indicative of the wider research movement which is rapidly drawing in the expertise of Human Factors specialists around the world, that of man-machine integration.

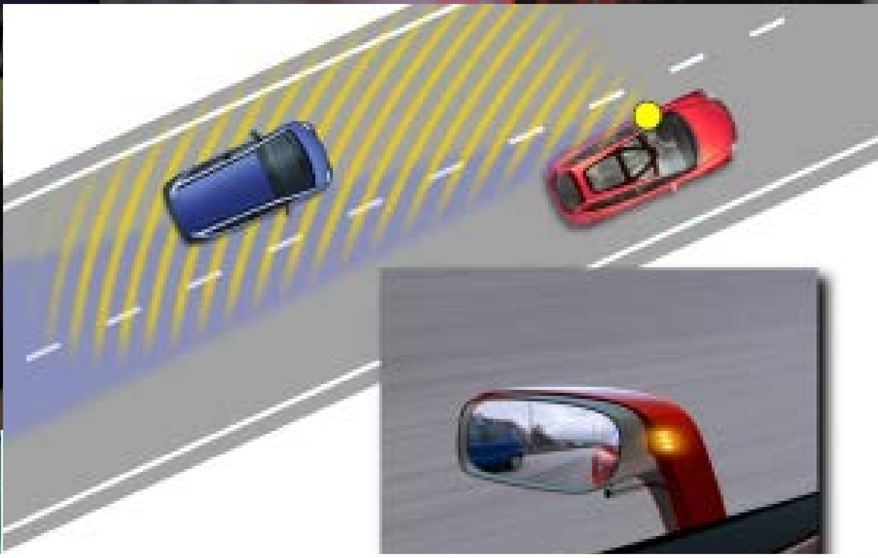


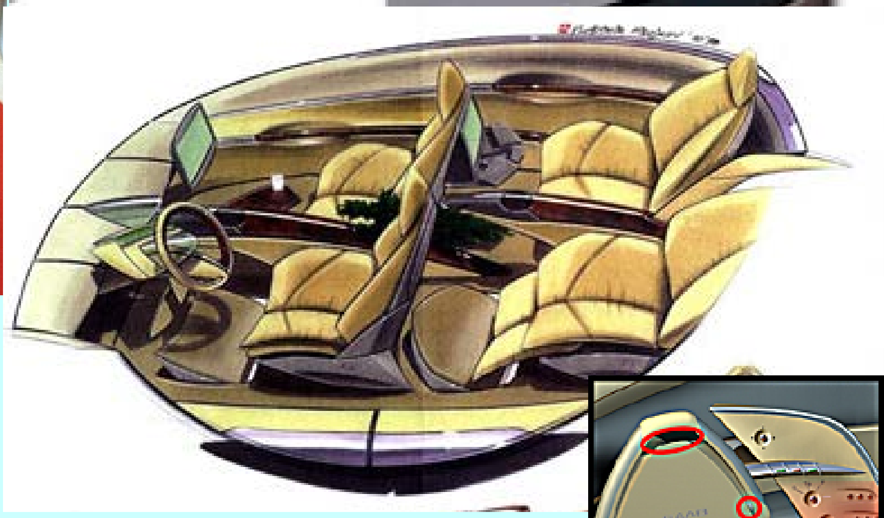


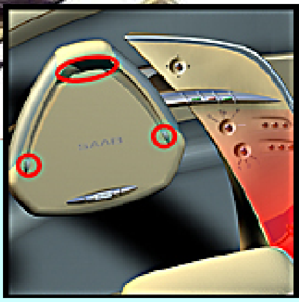
Man-Machine Integration



Many systems are under development which blur the traditional distinctions between machine and human.



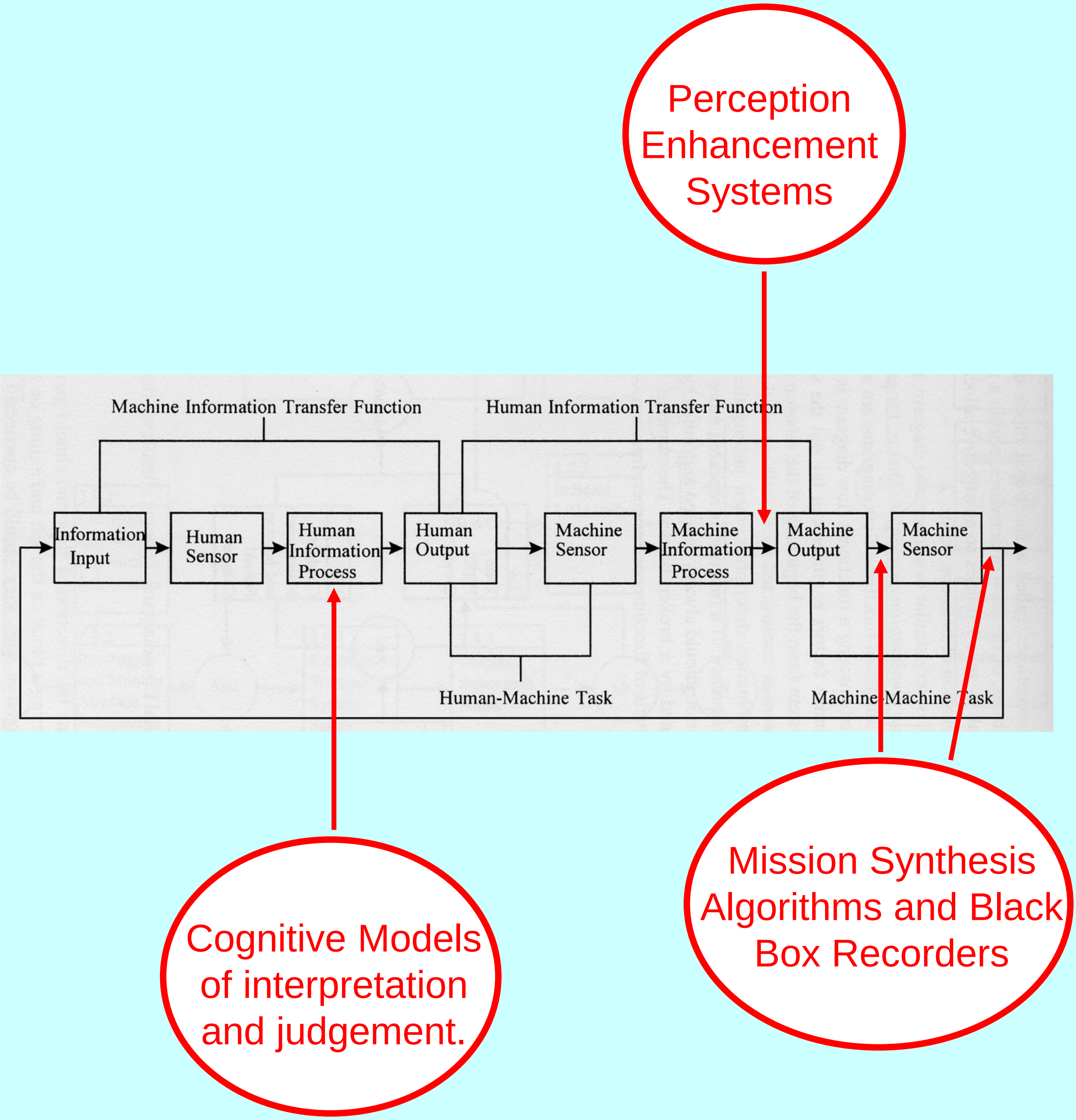




Man-Machine Integration

In vehicles new interfaces are being developed which integrate the functions of humans with those of the machine.

Research Being Performed at Sheffield University



Perception Enhancement Systems

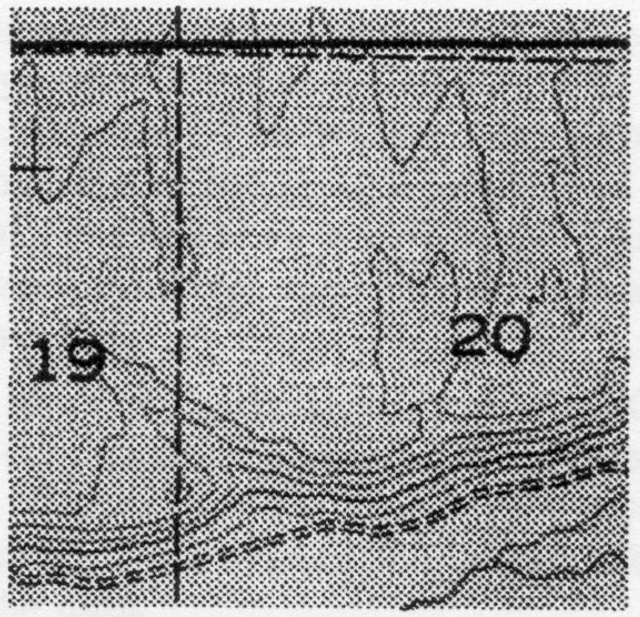


Figure 1: The 512 × 512 map image

An interesting example of a PES is the Human-Machine Perceptual Cooperation (HMPC) paradigm described by Quek and Petro in 1993.

By means of a smart cursor the computer cartography system acts as an intermediary between the map data and the human reader.

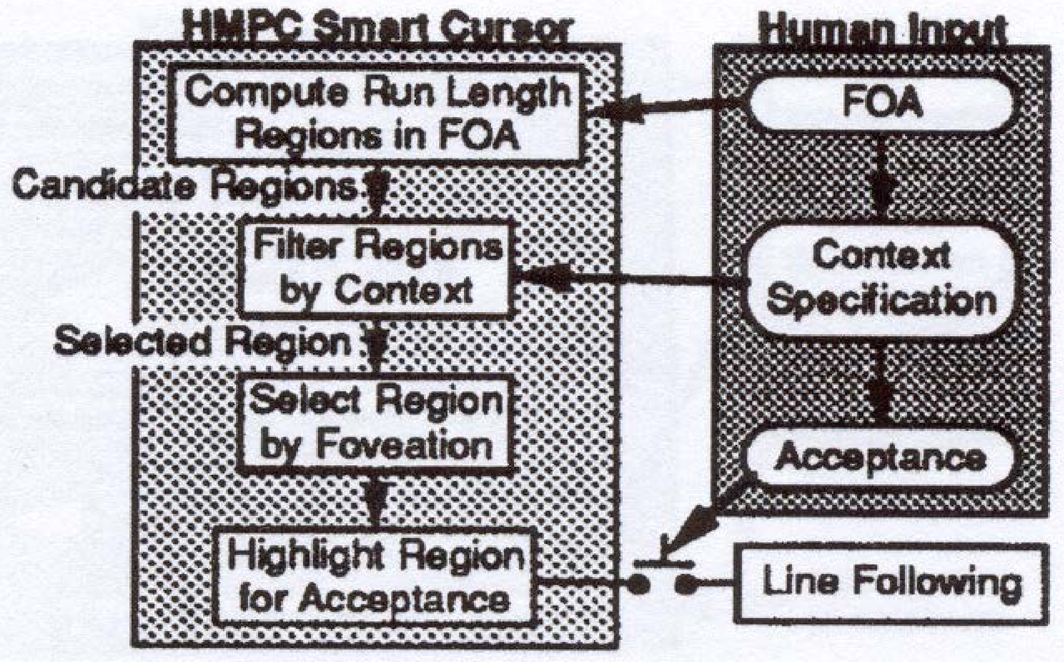
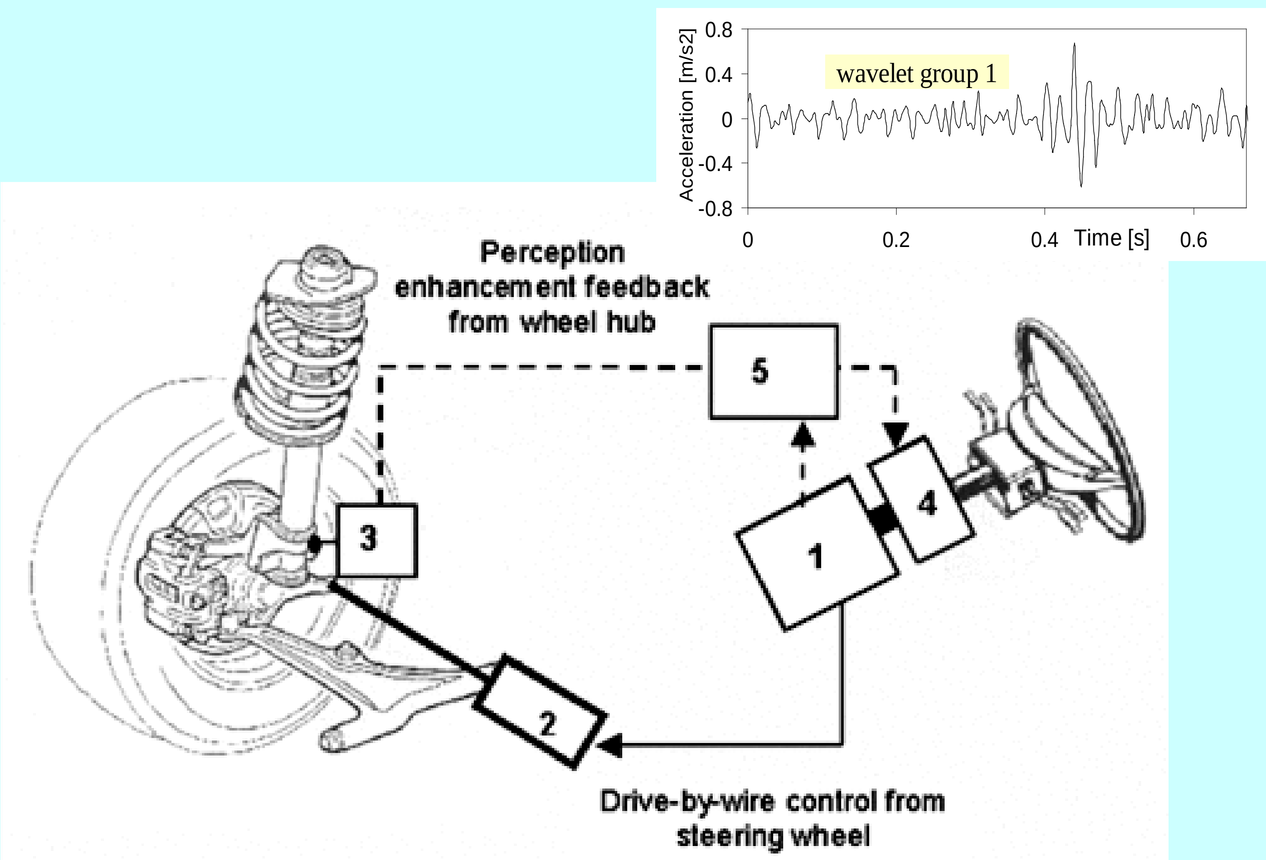


Figure 3: FOA processing for line extraction

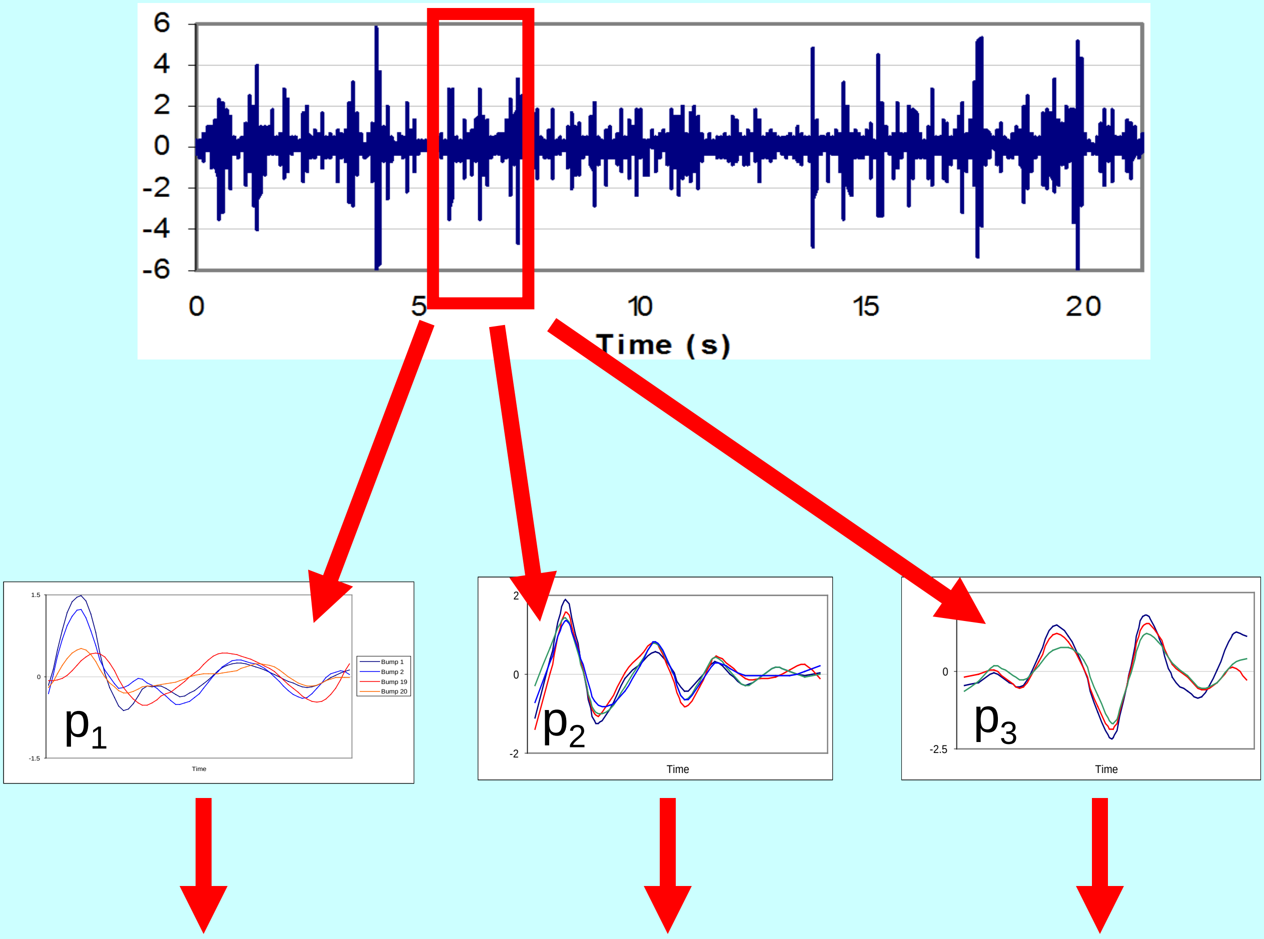
Perception Enhancement Systems

The term *Perception Enhancement System* can be used to describe any device which optimises the feedback of vehicle movements and vehicle interaction with the environment to the driver. Such systems treat the data from an information theoretic point of view, and optimise the machine-human interface so as to make the vehicle feel more like an extension of the driver's body.



Sheffield research is attempting to define the frequency bands containing the vehicle dynamic state information so that steering components can be optimised to better transmit the information.

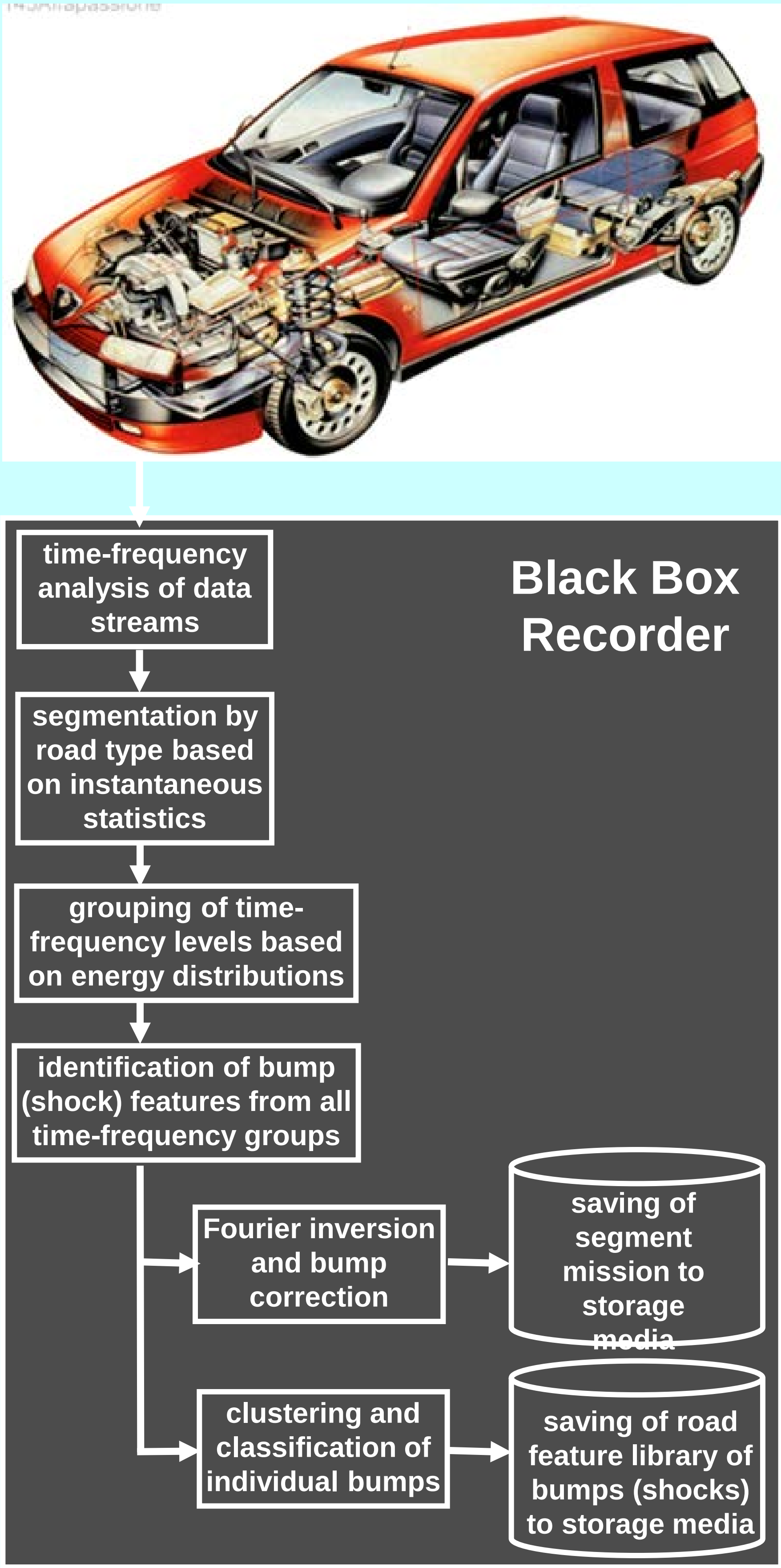
Perception Enhancement Systems



$$H = -\sum_{i=1}^{n} p_i \log p_i \quad \textit{bits per symbol}$$

A possible basis for a vehicular steering PES might be an *Information Entropy* measure used in conjunction with a library of road features.

Mission Synthesis Algorithms and Black Box Recorders



Sheffield University has developed two generations of Mildly Nonstationary Mission Synthesis algorithms for summarising long vehicle road data records.

MNMS uses Fourier methods, Orthogonal Wavelet Transforms, wavelet grouping procedures and bump (shock) correction procedures for producing short signals which maintain the statistical properties of the original data.

Current research is developing algorithms for instantaneously subdividing acquired data into segments of uniform statistical content.

Current research is also developing bump (shock) event clustering and classification procedures which are optimised for either comfort or fatigue analysis purposes.

Cognitive Models of Interpretation and Judgement

Research is now starting in collaboration with the Department of Psychology to develop cognitive models of the processes by which humans judge the vehicle state and rate performance and quality. Such models imply the development of a database of background vehicle data against which new stimuli are processed and judged.