Chapter 8:

HUMAN PERFORMANCE[*]

Introduction

As you will find in this book, computer input device design, and use, reflects a variety of choices in multiple dimensions. Ideally, these choices would be guided human capabilities and limitations. In practice, however, the development of most devices has been more driven by available sensor technologies than human considerations. This "technology push (or gadget-driven)" approach needs to be replaced by a "demand pull (or human-driven)" one. (Jacob, Leggett, Myers, and Pausch 1993).

In order to practice a human-driven agenda, however, we need a systematic body of knowledge of human capabilities and limitations and the ability to relate these to relevant design dimensions. Unfortunately such type of information is scattered across many domains (experimental psychology, human motor control, human factors engineering, HCI, *etc*.) and published in a broad range of journals, conference proceedings and books. It is often difficult for a designer to access and assemble the requisite knowledge for the task at hand. And even when one can find the relevant literature, it is often contradictory or difficult to interpret. Thus, in this chapter we summarize and help interpret the key literature and provide pointers to key sources, with an emphasis on studies that are not generally widely known or available to HCI practitioners. Hopefully, the result will be the establishment of a stronger foundation from which the reader can make human-driven decisions.

An overview of human performance studies in manual input control

The study of human performance as a function of manual control device certainly goes beyond the HCI literature. The current interest in input devices is largely the result of the relatively recent

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advent of GUI style of interaction. However, the study human performance in relation to design variations of manual control devices has been a subject of research for a few decades before the GUI was ever thought of. This research was primarily driven by applications in vehicle control and aircraft piloting.

The first wave of human factors research on input controllers started in the 1940's and reached its apex in 1950's and early 1960's. Orlansky (1949) provided one of the earliest comprehensive studies in the discipline. He analyzed factors such as maximum forces that may be exerted by a human pilot, the gradient of control forces and the manner of human movement.

Researchers from the Applied Psychology Unit of the Medical Research Council in Cambridge, England, including K.J.W. Craik (Craik, 1943, 1944, posthumously published as Craik and Vince, 1963a, 1963b, after Craik's death in 1945), C.B. Gibbs (1954; 1962), E.C. Poulton (1974) and others, took leading roles in the early research on controls. These researchers were concerned with how human performance was affected by various type of controls. Gibbs, for example, hypothesised that isometric devices (force sticks) provide strong "proprioceptive discharge" in the human limb and therefore help the human operator's performance.[1] Poulton, on the other hand, took a position opposite to that of Gibbs.

Another notable group of researchers, the "Ohio School", including P.M. Fitts (1951), H.P. Bahrick (Bahrick, Fitts, and Schneider, 1955b), D. Howland and M.E. Noble (1953) made the most impressive theoretical contributions to the understanding of controls. Their central thesis was that human proprioception can be modelled by laws of physics. According to their theory, elastic loading on a control device augments the perception of displacement, due to the fact that the resistance force of a spring is proportional to displacement (Hooke's law). When a control device has viscous resistance, the human perception of velocity will be enhanced, due to the fact that viscous resistance is linearly related to velocity. Similarly, as revealed by Newton's second law, inertial resistance is proportional to acceleration, therefore the mass of a control device should augment the human perception of acceleration. This physics based model of proprioception was supported by a series of analyses and experiments (Fitts, 1951; Howland and Noble, 1953; Bahrick, Bennett, and Fitts, 1955a; 1955b; Bahrick, 1957). Notterman and Weitzman (1981) later confirmed this proposition in a more systematic manner.

The early research on controls was often concerned with dynamics. Aircraft, submarines and other vehicles all take time to respond to input according to their internal complex dynamics. Much research was devoted to developing and studying engineering tools to model dynamics transfer functions. Birmingham and Taylor (1954, cited in Notterman and Page, 1962) hypothesised that human tracking performance would remain unchanged, despite variations in control device properties, if there was no change in the overall transfer function relating the force applied to a control device to the system output. Notterman and Page (1962) conducted an experiment, however, that rejected Birmingham and Taylor's hypothesis. They studied systems that maintained the same overall transfer function (second order dynamics) but differed in where the dynamics were located within the control loop. In one system, second order dynamics were embodied in the input device's mechanical properties (elasticity, viscous damping, and inertia). In the other two systems, the input devices had negligible dynamics but the same second order dynamics were simulated in an analogue computer between the input device and the display. Notterman and Page demonstrated that the human operator had better performance with the first system, although mathematically the total system transfer function was comparable with the other two systems. They argued that the "local" (proprioceptive) feedback in the first system helped the subjects, since they could not only see the dynamic response from the visual display but could also "feel" the dynamics from the physical device.

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[1] *Proprioception* is the awareness of body position, or more literally, "knowledge of self." (Sheridan and Ferrell, 1974, p.9)

Whereas the first wave of human factors research on input was driven by the control of vehicles, the second wave was driven largely by issues arising from the manual control of complex systems, such as power plants or complex process control. In this work, how humans handled the plant dynamics became more of a central theme in the research than the properties of input device themselves. Engineering models (particularly classical and modern control theories) were applied to describe and predict human behaviour in such complex systems. Sheridan and Ferrell (1974) provided a comprehensive summary of these efforts. In more modern control systems, however, automation of machines has reduced concern for the dynamics aspect of manual since much of the low level dynamics can now be handled by automatic controllers and the human's role has been increasingly elevated to supervisory tasks (Sheridan, 1988, 1992b). Today's design of controls is therefore more concerned with facilitating human information input (or spatial instructions) into computer systems.

Research into input control has a strong two-way connection with the study of human motor skills. On the one hand, knowledge from human motor control research has been applied to the design of control interfaces. On the other hand, many researchers have used different input control devices and manual control paradigms as vehicles for studying human motor control behaviour. The previously mentioned research by Gibbs and by Fitts and his are examples of the latter. Likewise, studies of tracking provided the foundations for Krendel's and McRuer's successive organization of perception (SOP) theory, which hypothesised the general trend of human skill shift from closed loop to open loop behaviour (Krendel and McRuer, 1960). Pew’s (1966) proposed hierarchical organization of human motor control was also based on tracking research.

Interest in research on the properties of controls decreased in the mid-1960's; however, A. A. Burrows (1965) made a plea to continue studies on "control feel" and its related variables. He argued that "one would expect the relationship of the hand to the controlled element, being at the one time both an input and output, to be a fruitful area for research", but the reality is that little was well understood. He pointed out that the reluctance to conduct research in this area is understandable in view of the immensity of the possible interactions among the many dimensions of control feel.

In 1974, E.C. Poulton published a comprehensive review of human tracking skills and manual control. His book (Poulton, 1974) was written in a very empiricist style, placing heavy emphasis on experimental data rather than theoretical issues and models. This was criticized at the time by other researchers (e.g. Pew, 1976). In retrospect, Poulton's inclination towards empirical results was not necessarily unwise. Models and theories in research often change with the varying cultures in the scientific community, but empirical data remain valuable. Taking human motor control as an example, cybernetic models were widely applied in early research, as evident in (Brooks, 1981) which surveys motor control research in the 1960’s and 1970’s, but decreased dramatically in later journal publications. Instead, artificial neural network models are currently on the rise.

Another important feature of Poulton's book was his critical discussion of "asymmetrical skill transfers" likely caused by within-subjects designs of experiments in the research literature. In within-subjects experiments, the same group of subjects is assigned to all experimental conditions; that is, each and every subject performs all experimental conditions. In between-subjects experiments, on the other hand, the subjects are divided into subgroups. Each subgroup of subjects perform in only one experimental condition. A within-subjects design needs fewer subjects than a between-subjects design and is therefore more commonly used. Apparently, in within-subjects experiments, subjects may carry over some effects, such as skills or fatigue, from earlier conditions to later conditions. In order to overcome this possible transfer effect, the sequencing of the experimental conditions in within-subjects designs is usually “balanced” by assigning subjects to the conditions in such a way that all experimental conditions have an equal number of times of being first, second, etc., or last condition. Poulton argued that although such an arrangement may balance the sequence of the conditions, it does not guarantee that the actual skill transfer from one condition to another is “symmetrical”. When transfer is asymmetrical, biased results can be produced. Poulton claimed that "once the biased results (due to asymmetrical skill transfer) are discarded, there emerges a clear and sensible description which differs in many respects from current views and practices". Asymmetrical skill transfer could indeed be a problem, but whether its effect is as important as Poulton believed is debatable. His repeated warnings (Poulton, 1966, 1969, 1973, 1989) have not been widely accepted by psychologists and human factors researchers, as within subject designs continue to be used frequently in experimental research.

Since the late 1970's, another wave of studies on input controls have been carried out as part of the research on human computer interaction (HCI). Card, English, and Burr (1978) conducted one of the most well known studies on the performance differences between various computer input devices (mouse, trackball, joystick, stylus, etc.). Card and colleagues also established the Fitts' law paradigm as the *de facto* standard task for computer input device research, even though Fitts' law is only one of the many theoretical products of decades of human motor control studies. The Toronto Input Research Group (IRG), which the authors founded, has attempted to take input research from a broader perspective. We strongly advocate the critical relationship between the physical input devices and the higher level cognitive processes. Communicating this view is one of the main motivations for writing this book.

Basic design dimensions that may influence human performance.

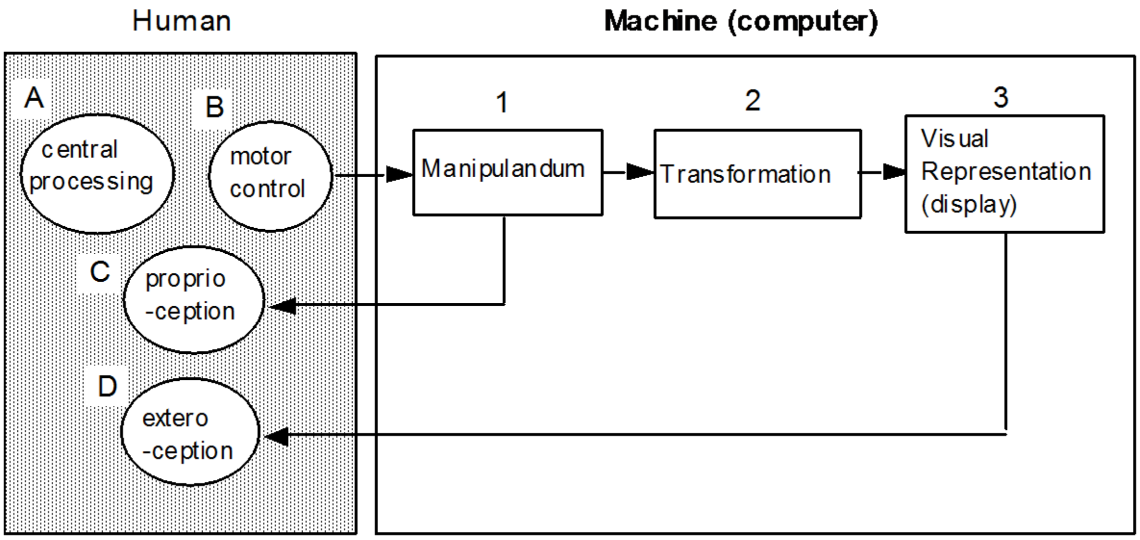

Figure 1

Design variations in many parts of an interactive system can influence how a user conducts input control tasks. Figure 1illustrates the major components involved when a user exchanges information with a computer system (or any machine in general). Block 1 in Figure 1is the physical control interface between the user's limb and the machine (computer). This physical interface, the most often considered part of input control systems, is also called a *manipulandum* in many fields. Note that the information transfer between the human limb and the “input” device is in fact bilateral.[2] In one direction, the user's motor actions manipulate the device and these

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[2] This point is further reflected in the discrepancy in terminology between different disciplines. In the psychology literature, which takes a human-centric posture, “input” refers to input to the human, whereas the

actions are transformed into instructions for the computer. In the other direction, the user also receives certain control feel information *via* proprioception from the physical device. This bilateral nature of an input device cannot be overlooked. For example, an important issue is what resistance[3] the device should have in order to produce proper control feel. Should the designer choose a freely moving device such as a mouse or a trackball, a device with a certain type of movement resistance such as an elastic device, or a device with infinite resistance (isometric joystick, such as the control sticks used in many notebook computers)?

The design of the physical size and shape of a physical device also has implications towards which the particular muscle groups (limbs) used in manipulating the device, including the wrist, the arm, the hand, and the fingers. For example, a relatively small handle may afford the user to use the fingers. Are some body joints more suitable than others for computer input device manipulation?

These are both issues that will be discussed in this chapter.

Finally, the interaction process goes beyond the physical device itself. Block 2 in Figure 1represents the transformation from user's output to the computer display interface. There are many alternatives in designing this transformation to map the output of the physical device to object movement. Later in this chapter we will review studies related to such transfer function design.

Isometric versus Isotonic Devices

Defining the Terms

The human limb can send and receive information through either force/torque or displacement/rotation. Correspondingly, an *isometric* device connects the human limb and machines through force/torque while an *isotonic* device does this through movement.

Isometric devices are also called pressure devices or force devices. Literally, the word isometric derives from the Greek "isos" meaning "same" or equal and "metric" meaning "measure" or in other words, constant length, or non moving. According to *Webster's Ninth New Collegiate Dictionary,* isometric means "of, relating to, or being muscular contraction against resistance, without significant shortening of muscle fibres and with marked increase in muscle tone". By this definition, an isometric device is a device that senses force but does not perceptibly move.

Isotonic devices are also called “displacement devices,” “free moving devices” or “unloaded devices.” From the Greek, the word isotonic means equal "tonikos", or “constant tension.” According to *Webster's Ninth New Collegiate Dictionary*, isotonic means "of, relating to, or being muscular contraction in the absence of significant resistance, with marked shortening of muscle

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human-factors literature takes a more machine-centric approach where “input” refers to input to the machine. Besides alerting the reader to possible conflicts in terminology, this points out that the machine's output is the human's input, and *vice versa,* and that in interaction, both nearly always coexist.

[3] The on-going discussion is concerned only with input control devices which produce various passive resistance forces to movement, such as elastic and isometric devices. Much work has been done in designing input devices that have *active* force reflection. See (Shimoga 1993a,b) for a survey on force-feedback devices. See (Brooks, Ouh-Yong, Batter, and Kilpatrick 1990) for force feedback applications in scientific visualisation. See (Massimino and Sheridan 1993) for substituting force reflection with audio feedback in teleoperation.

fibres, and without great increase in muscle tone - compare *isometric*". An isotonic device should have zero or constant resistance. The mice that are used with most of today's computer systems are examples of isotonic devices.

Between the isometric (infinite resistance) and the isotonic (zero or constant resistance) are devices with varying resistance. When the device’s resistive force increases with displacement, the device is *elastic*, or spring-loaded. When resistance increases with velocity of movement, the device is *viscous*. Similarly, when the resistance increases with acceleration, it is an *inertial* device. In practice, all devices have some inertia. However, the device's inertia is usually ignored when it is relatively small compared to the inertia of the human hand or when the initial resistance is relatively small compared to other forms of resistance (e.g. elastic).

Some authors also use the term "moving device" as a short form for free moving (isotonic) device. Other authors have used it for all devices that move ("anisometric"). However, *Anisometric* devices actually include free moving (isotonic) devices and elastic, viscous or inertial devices, as well.

The peculiarities of many real world applications may favour either isometric or isotonic devices. For example, implementation with one device might simply be less costly than the other at a particular phase of technology development. Alternatively, certain work environments may not allow free hand movements due to physical workspace constraints or motion noise (vibration), such as in vehicles or aircraft. It may also be that in certain applications, the target users are predisposed to one technology or the other as a result of the idiosyncratic skills of their profession. Such special cases nonwithstanding, the general performance differences between isometric and isotonic devices are still of both theoretical and practical importance.

The Literature on isometric versus isotonic devices

Early research comparing isometric devices with isotonic devices is well reviewed in Poulton (1974). Poulton's hypothesis was that isometric control (“pressure control” in his terminology) is in general advantageous whenever time is short and fine accuracy not critical, but disadvantageous when slow, accurate positioning is required. According to him, an isometric device has no travel time, which should make it quicker to control, but it cannot be adjusted very accurately because it does not provide the human operator with any *displacement cues* proportional to its output. In contrast, either an isotonic or elastic device ("moving control" in his terminology) does provide the displacement cue for accurate control.

Contradictory to Poulton's view, many other researchers, including Gibbs (1954) and Burke and Gibbs (1965), argued that an isometric device should in fact provide stronger "proprioceptive discharge" and therefore should produce better performance for tracking tasks. Based on his experiments on manual tracking, Gibbs went on to advocate a *closed-loop*[4] theory of motor control, since isometric controllers were believed to give more feedback to support closed-loop behaviour. Gibbs’ work has been influential in the motor control literature. For example, Keele

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[4] As introduced in Chapter 7, *Closed-loop* motor control is that where there is constant feedback as to the result of the action to date which is used to govern the control of the rest of the action. Closed-loop behaviour is normally associated with *fine motor control.* It is in contrast with *open-loop* motor control, also commonly known as *ballistic* motor action, where the action is governed by an initial “command” rather than any ongoing feedback. This is most commonly associated with *gross motor action*, such as throwing a ball. As the literature reviewed in this chapter should make clear, however, there is controversy as to both the existance of these behaviours, their nature, where they come into play, and their effect on performance.

(1986) cited Gibbs and promoted "the better quality and greater rapidity of kinesthetic information in isometric muscle contractions as opposed to isotonic contractions".[5]

Note that both views, represented by Poulton and Gibbs respectively, emphasised the importance of feedback. What they disagreed on was which class of device provides the stronger feedback. Gibbs believed that an isometric device should give stronger feedback due to the stronger "proprioceptive discharge" since force is being used. Poulton, on the other hand, believed that anisometric devices give stronger feedback due to the "movement cue".

Poulton (1974) compiled a comprehensive list of studies dating from 1943 to 1966. Out of 17 investigations that he cited, 12 strongly favoured pressure control, two slightly favoured pressure control and only three slightly favoured anisometric (isotonic or elastic) controls. These studies were conducted under various conditions, ranging from rate control to position control, from high frequency tracking to slow ramp tracking, from compensatory to pursuit displays. Other reviews, such as Boff and Lincoln (1988, section 12.421), also give similar conclusions that isometric joysticks yield better performance (e.g. smaller tracking error).

In his speculations upon reasons for this contradiction to his hypothesis, Poulton pointed out that most of the studies used the balanced treatment (within-subjects) experiment design. As has already been discussed, he has been strongly against this type of experimental design in many of his publications (Poulton, 1966, 1969, 1973, 1974, 1989). With a within-subjects design, he argued, the actual skill transfer from one condition to another might not be symmetrical, even when subjects' exposures to the two conditions are equalised. In particular, for the case of isometric vs. isotonic control, the skill transfer might favour the isometric control. Poulton also noted that isometric devices are always spring centred while isotonic controls are not and he thus suspected that it might be the spring centring that caused the performance difference. Poulton (1974) concluded that in order to reach a definitive verdict between isometric and anisometric devices more experimental research was needed. Unfortunately, no further studies that explicitly followed Poulton's analysis have been found.

Notterman and Tufano (1980) took Gibbs' belief in the superiority of isometric kinesthetic information and tested the so-called *inflow-outflow* debate in human motor control. *Inflow theory* proposes that human motor action fundamentally relies on feedback, the information flowing into the central nervous system (CNS) from the periphery. In contrast, *outflow theory* proposes that human motor control is primarily a result of executing motor commands flowing out of the CNS to the peripheral motor organs. On the basis of Gibbs' conclusion that isometric devices should give stronger feedback than isotonic devices, Notterman and Tufano argued that the relative human performance with an isometric device versus an isotonic device would be an indicator of the validity of inflow versus outflow theory. If superior performance were to be found with isometric devices, implying stronger feedback does improve human motor performance, inflow theory would be supported. On the other hand, if superior performance with isotonic devices were to be found, implying that human motor performance is actually better without or with less proprioceptive feedback, outflow theory would be supported. What Notterman and Tufano actually found was more complicated: (1) the isometric condition was better for randomly moving targets (0.33 Hz Gaussian noise) while the isotonic condition was better for predictably moving target (0.5 Hz sine waves). (2) the isotonic stick was better than an elastic stick at the beginning of training but worse by the end of training. They concluded that the inflow and outflow dispute was overly simplified. "Subjects profit from whatever exteroceptive and proprioceptive cues are

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[5] *Kinesthetic feedback* is a particular form of proprioceptive feedback that means literally, “sense of motion.” (Sheridan & Ferrell, 1974, p.9)

available and efficacious and they organise their behaviour accordingly".[6] Since Gibbs' notion of isometric superiority in proprioceptive feedback is questionable in any case, Notterman and Tufano's study did not actually have a solid basis for testing the inflow-outflow debate.

Jones and Hunter (1990) conducted a systematic study on elastic resistance ranging from isotonic to isometric in a step tracking experiment. The major findings of their study confirmed what many early researchers had believed: stiffer devices can be used to generate faster responses, as indicated by (1) shorter times to reach 50% step responses and (2) smaller human-machine closed loop system delays. However, the implications of the relative rapidity of isometric (or stiffer) devices should be interpreted very carefully, this work being a classic example of the ubiquitous *speed-accuracy tradeoff* at play[7]. What Jones and Hunter (1990) also found was that as stiffness increases, subjects' accuracy tended to decrease. This means that the shorter 50% response time may not result in better performance. A "fast" system with large overshoot may have a shorter response time, but the final settling time (time to reach and remain within 2% of the final target) could be even longer than a "slower" system. Unfortunately Jones and Hunter did not report on the settling times for each condition tested.

Using a two dimensional positioning task, Mehr and Mehr (1972) did a comparative study between (1) a spring centred joystick in position control mode, (2) an isotonic joystick in rate control mode, (3) a thumb-operated isometric joystick in rate control, (4) a finger operated isometric joystick in rate control mode, and (5) a trackball. It was found that condition (4), which involved an isometric device, showed superior performance (in terms of both completion time and error) compared to condition (2) which employed an isotonic device. However, one can not identify the cause of the performance differences since the three factors, i.e., resistance, transfer function and body parts, were all confounded in that study[8].

Dunbar, Hartzell, Madison, and Remple (1983) presented a comparison study in the context of helicopter control. Conventional helicopters have three separate controllers, namely cyclic, collective, and rudder pedals, controlling pitch/roll, heave, and yaw respectively[9]. Dunbar and colleagues compared a set of conventional separated controls with two integrated controllers, one isotonic and one isometric, in a 3 axis (pitch, yaw, roll) compensatory tracking task. Under all three levels of task difficulty (as defined by bandwidth of the signal being tracked), the RMS

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[6] *Exteroceptive feeback* (knowledge of that which is external to one's self) is the compliment of proprioceptive feedback (knowledge of self).

[7] This is an issue that should never be far from the reader's mind. Whenever data are encountered which present performance time results without accuracy information, or *vice versa,* a large red flag should pop up. Performance time data cannot be compared without being normalized for accuracy, nor accuracy data unless normalized for performance time. An example of how one can approach normalization within the speed/accuracy tradeoff is seen in MacKenzie (1991 & 1992), which was discussed in the Fitts Law section in the previous chapter.

[8] In interpreting this type of comparative literature, the reader is also cautioned to keep in mind that there can be significant differences in performance even among different devices within a particular class (such as trackballs, or isometric joysticks). One should always question whether the primary influences on performance are those being tested. It may well be that the results reflect the idiosyncracies of a particular isometric joystick (size, shape, placement, transfer function, etc.) than isometric devices as a class. Understanding such issues is a running theme throughout this book.

[9] Shumin: these are nearly all new terms. Can you fill out this footnote with clarification?

tracking errors with the isometric controller were found to be significantly smaller (i.e. better performance) than the RMS errors with the isotonic controller.

Dunbar and colleagues were surprised with the fact that the isotonic controller showed even worse performance than the conventional, separated controllers. The authors speculated on three causes for the results. (1) Display. A 2D, compensatory display was used in the experiment, with pitch error displayed along the y-axis, yaw error displayed along the x-axis, and roll error as angular rotation in the plane of the display. The authors believed that a compensatory display might have suited the isometric controller while a pursuit display might been more suitable for the isotonic controller. (2) Task. The tracked target (signal) had relatively high bandwidth and the isometric controller may have an inherently higher bandwidth than isotonic controllers. (3) Implementation. The gains were not necessarily set at an optimal value for every type of controller.

Ware and Slipp (1991) did an informal comparison study where the task involved navigating trough 3D virtual space. They used a 6 DOF Spaceball™ (isometric) and a 6 DOF Flying Mouse™ (isotonic) to control the velocity of the user's viewpoint. Subjects were asked to navigate through a tunnel simulated in a graphical display. They found that on average, with the isotonic device traversal times were 66% of those obtained with the isometric one. The subjects also did a free scene exploration task and reported their subjective evaluations. Subjects reported that they felt that they were only able to control six DOF simultaneously with the isotonic controller. They reported that the isometric controller only afforded effective control over only one dimensional translation or rotation at a time. However, the users also complained of arm fatigue with prolonged use of the six DOF isotonic device, but not with the isometric one.

To summarise, the literature on the relative advantages and disadvantages of isometric versus isotonic devices has not been conclusive. Some reports support isometric devices while others support isotonic devices. The definitive answer may depend upon dimensions of the controllers other than devices.

With regards to the response speed, it resistance and also on the tasks used for the experiment. Bandwidth (response speed) and extent of feedback have been the two major underlying factors that researchers have believed to account for the theoretical differences between isometric versus isotonic can easily be concluded that human response with an isometric device is faster than a comparable isotonic device, since no transport of limb or device is needed. However, whether humans can effectively make use of this rapid response, while maintaining acceptable accuracy, is questionable.

With regards to the feedback, in the literature just reviewed, there appears to be a tacit agreement, either explicitly or implicitly, that proprioceptive feedback from the control device is a facilitator of control actions. However, different researchers disagree on which device actually provides stronger feedback: the isotonic devices that afford movement cues or the isometric devices that afford force cues? This question should be addressed in the neuromotor and psychomotor control literature. More theoretically, whether feedback is indeed needed for manipulation control is also a relevant question. This again is in the domain of human motor control. We will discuss these issues in later sections of this chapter.

Analysis and Literature on Position versus Rate Control

Theoretical Analysis of Position versus Rate Control

Position control refers to the control mechanisms by which the human operator controls object positions directly. More precisely, the transfer function from human operator to object movement in position control is a constant (i.e., a *zero order* transfer function). In contrast, *Rate control* maps human input to the *velocity* of the object movement. In other words the transfer function from human input to object movement is an integral (i.e., *first order* transfer function).

It has been conclusively demonstrated that position control and rate control are both superior to higher order control[10] in most tracking tasks (Wickens, 1992; Poulton, 1974*). Acceleration control*[11], for example, is usually more difficult and unstable than position and rate control. This has also been verified in 6 DOF placement tasks (Massimino, Sheridan, and Roseborough, 1989).

The performance difference between position and rate control is less obvious. Much work has been done in their comparison. The majority of these studies concluded that rate control is relatively inferior. From an isomorphism point of view, position control can be considered more direct (more isomorphic) than rate control *as long as what is being controlled is the position (as opposed to the size, for example) of the tracker*. In this case, it has 1-to-1 (or 1-to-K) correspondence between input and output, requiring little mental transformation in generating control actions (Figure 2). It therefore provides a more intuitive control mode to the human operator. Note that the directness of position control is still subject to other design considerations, including stimulus-response compatibility (Fitts and Seeger, 1953).

Rate control, on the other hand, controls movement through velocity. As illustrated in Figure 2, input control patterns for rate control are more complex than for position control. In order to cause a change of state from one level to another, a pair of reversal control actions has to be given. Figure 2 shows only idealised control patterns. In reality, control motions will not be instantaneous but the basic feature of paired reversal inputs for rate control (speed-up, maintain a level of control and then slow down) remains. Note that in rate control, the user controls both the magnitude and the duration (timing) of the input signal. This can be considered an disadvantage in terms of complexity on one hand, and an advantage in terms of precision, on the other: the final cursor position does not depend on the resolution of the input transducer alone.

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[10] Shumin: I understand that acceleration control is one example, but can you help clarify the essence of the issue/meaning here? I think that stated this economically (without footnote at least) it will be missed.

[11] Shumin: please give brief explanation.

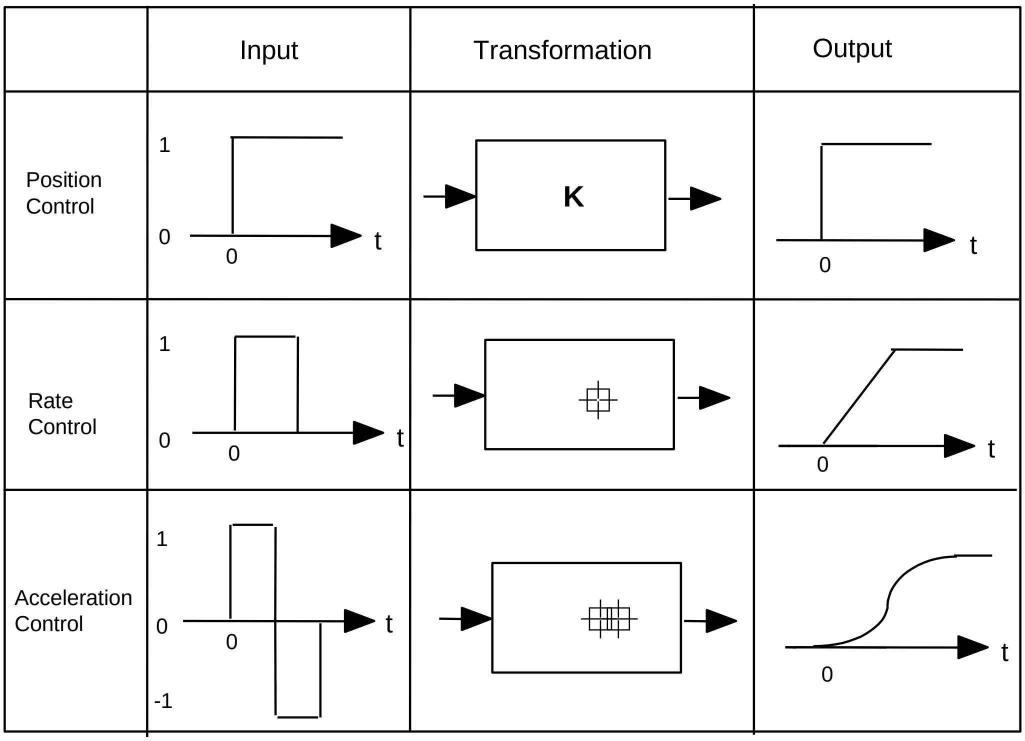


Figure 2: Idealised control inputs (left column) for obtaining step changes in output level (right column) for position, rate and acceleration control

Position control also has its conceivable disadvantages relative to rate control. First, it transfers all human limb movements, whether voluntary or involuntary, to the manipulation task. In contrast, the low pass filtering effect introduced by the integral function in a rate control scheme will suppress many high frequency involuntary noises. Second, by definition, rate control lets the user control the velocity of the controlled object, resulting in smoother movement. With position control, on the other hand, it is more difficult to maintain control of the velocity of the movement, increasing the likelihood of jerky motions. Third, with position control, the maximum operating range is limited unless clutching or indexing (Johnsen and Corliss, 1971) is adopted, whilst rate control has an effectively unlimited operational range (auto-indexed). This last point is particularly important for computer input devices such as small Trackball or trackpad, which have very limited range in each stroke of manipulation and frequent reclutching (lifting finger and reengage the input device at a new spot) diminishes the performance of these devices.

The Literature on Position versus Rate Control

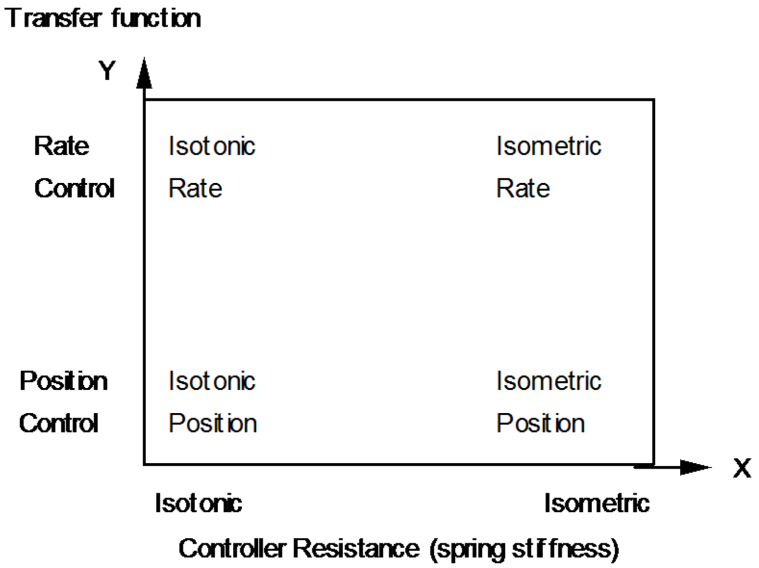
The literature on position and rate control is more consistent than that of isometric versus isotonic devices. It is generally found that position control is superior to that of rate control. Lincoln (1953), in one of the early studies, showed that subjects' tracking performance (time on target) with position control was substantially better than with rate control. The experiment was done with a mechanical manual tracking system described in (Lincoln and Smith, 1950). Subjects tracked an irregularly moving target mounted on the circumference of a rotating wheel with a cursor mounted on a smaller concentric wheel driven by a hand crank.

Jagacinski, Hartzell, Ward, and Bishop (1978) studied position control versus rate control in a Fitts' law task, both with an elastic joystick. They found that, in Fitts' law modelling, the linear regression line of rate control mode had a steeper slope than that of position control mode and the two linear regression lines intersected at 4.7 bits of index of difficulty. When the index of difficulty was below 4.7 bits, position control was slower. Above 4.7 bits, rate control was slower. In other words, position control was better for higher index of difficulty (precise) tasks while rate control was good for lower index of difficulty (coarse) tasks. However, two years later in a very similar study, Jagacinski and colleagues (Jagacinski, Repperger, Moran, Ward, and Class, 1980) found that rate control consistently gave lower performance than position control at all levels of difficulty.

Driven by teleoperation applications, Kim, Tendick, Ellis, and Stark (1987) did a comprehensive comparison study of rate control versus position control with two types of tasks. One was a 2 DOF pick and place task. The second was tracking a one dimensional sinusoidal movement. They ran only two subjects in their experiments, much less than the minimum number of subjects (six) recommended for this type of research by Poulton (1974). Some of the primary researchers seemed also to have served as their own experimental subjects. Nevertheless, this was still a very comprehensive (in terms of factors investigated) and valuable comparison of rate versus position control. In their first task, position control yielded better performance than rate control, with completion time about 1.5 times faster for the position control. This was true with both an isometric joystick and an isotonic joystick, even though the magnitude of the difference varied with the joystick type, with the difference between position and rate control being larger when the joystick was isotonic. Kim et al concluded that rate control generated longer mean completion times because rate control required a pair of opposite movements to reposition the manipulator while position control required only one movement. In their second task (sinusoidal tracking), position control had consistently smaller RMS error than rate control.

Compatibility between device resistance and transfer function

The previous two sections analysed the pros and cons of isometric versus isotonic devices and position versus rate control and reviewed relevant literature. One outstanding controversy with regards to isotonic and isometric devices, will be explained in light of more recent studies.



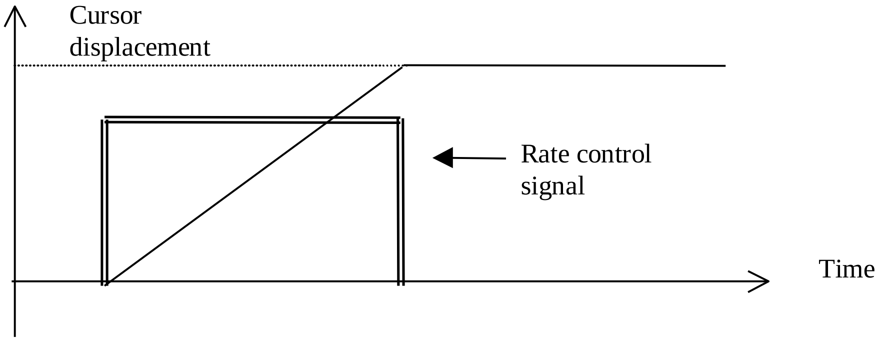


Figure 3: Rate control contains paired reversal actions, Note that the control patterns are idealised (vertical acceleration).

As discussed in Figure 3, rate control requires paired reversal actions. The user has to go through a cycle of start - speedup - maintain velocity - slow down - stop. With an isotonic device (such as a mouse), the latter half of the cycle, slow down and stop, has to be executed in such a way that when the cursor is approaching a target, the user has to return the isotonic device to its null position with correct timing. When returned to the null position too early, the cursor would not hit the target (undershoot). When returned to the null position too late, the cursor would overshoot.

With an isometric device, on the other hand, the self-centring scheme will automatically bring the control action to zero once the human releases muscular tension. This means that part of the control task in rate control with isometric devices is performed automatically by the device itself.

In position control mode, the self-centring effect with isometric devices does not work as an advantage, since position control normally requires control movement in only one direction. Instead, for such cases, the user has to *overcome* the self-centring force with isometric devices to maintain position. This may not only make it very difficult for the user to maintain output accurately, but can also cause fatigue.

What the above analysis indicates is that one should expect an interaction between device resistance (isotonic versus isometric) and transfer function (position versus rate). Isometric devices, in other words, are more simpler mental processing in position control, which should simply be a 1-to-1 (or 1-to-K) mapping in forming control actions. The latter may impose a higher compatible with rate control and isotonic devices are more compatible with position control.

With the two compatible modes, i.e. isotonic position and isometric rate control, the former should be the easier to learn. This is due to the presumed mental load on the user in forming the rate control actions, even though part of the work (returning to zero) is facilitated by the self-centring force of isometric devices.

A recent experiment in a six degree of freedom docking task (Zhai and Milgram, 1993a, Zhai 1995) formally demonstrated the interaction effect between device resistance (isotonic vs. isometric device) and transfer function (position vs. rate control). Figure 4 displays the means and standard errors of four input techniques over the four phases of the experiment. The ranks of the four techniques, as measured by average completion time over all four phases, was as follows: isotonic position (6.71 sec), isometric rate (6.97 sec), isotonic rate (10.55 sec), and isometric position (16.93 sec). Statistical comparisons between the four techniques shows that the performance differences between every pair of techniques were statistically significant, except the difference between the isotonic position and the isometric rate mode.

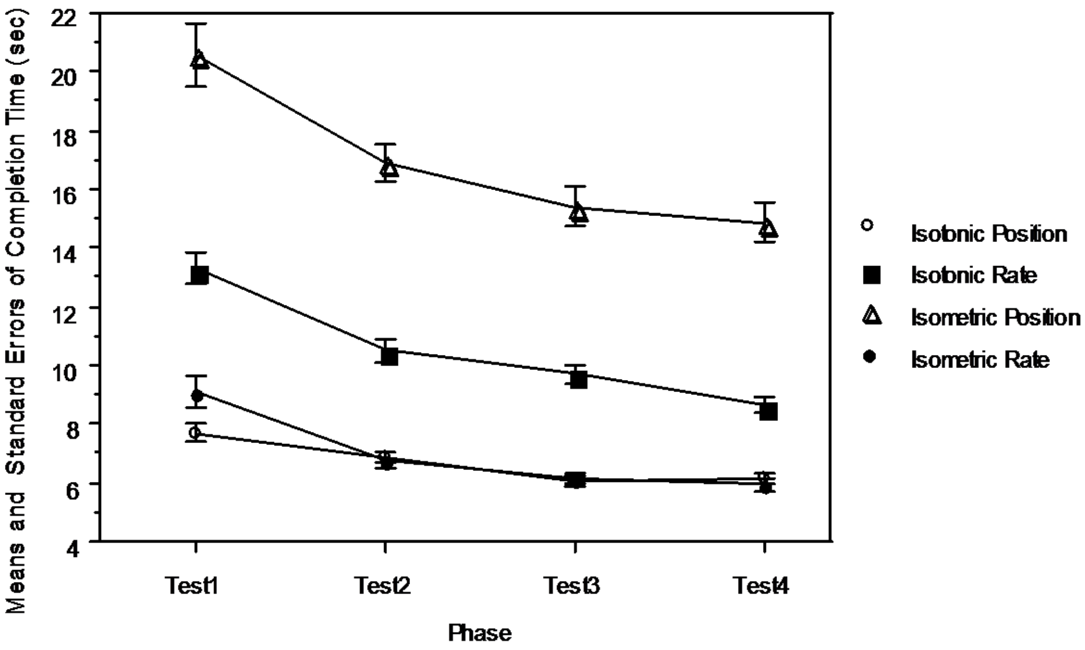


Figure 4: General results of 6DOF docking task (Zhai and Milgram, 1993a, Zhai 1995)

Statistically, even though both resistance (F(1,7) = 8.6, $p < 0.05$) and transfer function (F(1,7) = 12.8 $p < 0.01$) significantly affected completion time, the interaction between these two variables was much more significant (F(1,7) = 182.4, $P < 0.0001$), suggesting that simply to compare resistance (isometric versus isotonic) or transfer function (position versus rate control), as was found in some of the literature reviewed, is misleading. As illustrated in Figure 5, the isotonic device performed better than the isometric device in position control mode. In rate control, the opposite is true. Hence, we draw the following conclusion:

The compatibility principle in input technique design: for certain types of physical devices, the transfer function has to be designed accordingly. In particular, for isometric devices, rate control is more compatible. For isotonic devices, position control is more compatible.

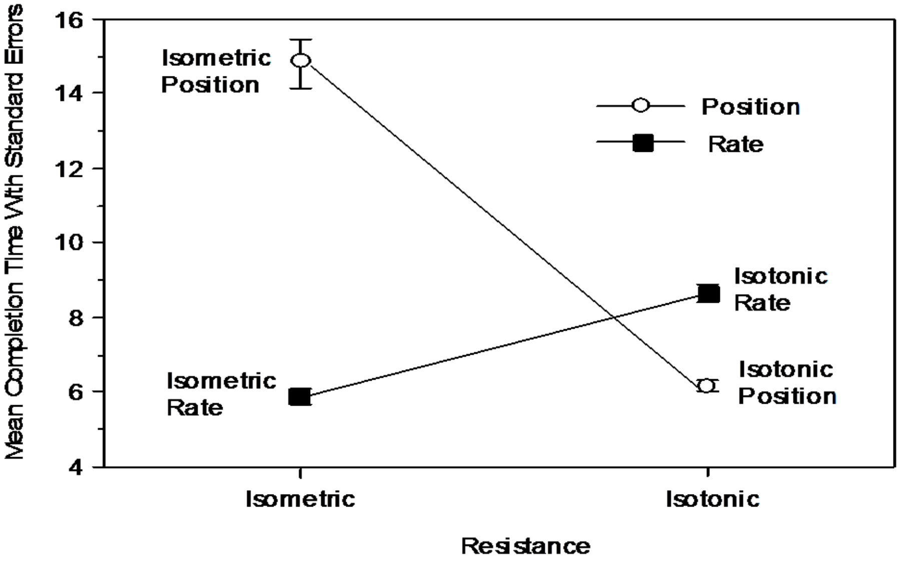


Figure 5: Interaction between resistance and transfer function (2D plot)

The above conclusion is based on an experiment in 6 DOF input control. Now let us reexamine many early studies with 1 or 2 DOF input controls. Taking Gibbs' studies as an example, Gibbs (1954) strongly advocated the superiority of isometric control, which indeed produced consistently smaller tracking errors than did isotonic control across tests spanning 6 days (15 minutes each day). In that study *rate* control was used as the transfer function in both isotonic and isometric conditions. Eleven years later, Burke and Gibbs (1965) repeated Gibbs' (1954) experiment in position control mode. They made the conclusion that the isometric device was still better than the isotonic device even in position control mode. However, this later conclusion was not as strong as the original conclusion with respect to rate control mode made in Gibbs (1954). As the authors claimed, "the relative superiority of pressure control was approximately 10 per cent in the present (position control) study, as compared with values of approximately 25 per cent to 50 per cent established by Gibbs (1954) (rate control)".

In checking the details of Burke and Gibbs (1965), it is questionable whether the conclusion of 10 per cent was reliable. Burke and Gibbs (1965) had a within-subjects design with two groups of 5 subjects. Group A tested with an isotonic stick in the first five days (15 to 30 trials per day) and Group B tested with an isometric stick in the first five days. Tracking errors with Group A (with isotonic position) were consistently smaller than Group B (with isometric position) in the five days. On day 6, the two groups switched devices and Group A (now with the isometric device) had better performance. On Day 10, the two groups once again switched devices and this time Group A (now with isotonic device again) had smaller tracking errors. Judging from their plot (Figure 3 in Burke and Gibbs, 1965), had the authors counted the performance difference only in last day, or the means of each device across all days, the isotonic device would have "won". However, the authors decided to draw their conclusion only from the data across Day 9 and Day 10, which supported their hypothesis of isometric superiority, even in position control mode.

Taking Lincoln (1953) as another example, the work is a classic study in demonstrating that position control is better than rate control, as cited in Poulton (1974). But in reviewing the study with the interaction pattern in mind, it is found that Lincoln used only an isotonic controller in his experiment. Clearly, these results might have been different had an isometric controller been used.

The interaction between device resistance and transfer function can also be found by examining the list of experiments reviewed in Poulton (1974, Table 15.3, page 308-309). Eight experiments on the list used rate control, and all supported isometric superiority. Of the two experiments that used position control, one made no conclusion, and one, which was Burke and Gibbs (1965), questionably supported isometric superiority. Poulton also surmised that Burke and Gibbs (1965) should have supported isotonic superiority, but from his methodological asymmetrical skill transfer point of view, rather than from the present interaction point of view.

The interaction pattern can also be seen in the data from Kim et al. (1987). In rate control mode, the isometric joystick performed much better than the isotonic joystick. In position control mode, the isometric joystick performed only slightly worse than the isotonic joystick. Unfortunately one can not draw a firm conclusion from their data, since only two subjects were tested.

There are also exceptions to the interaction pattern found in the current study.[12] For example, Dunbar, et al. (1983) found that an isometric 3 DOF controller produced lower RMS errors than an isotonic controller, even when position control mode was used.

Between the two compatible modes, namely the isotonic position control and the isometric rate control, *isotonic position control is more intuitive than isometric rate control.* The user can form control actions more directly with position control than with rate control and therefore it is easier to learn. On the other hand, there are several advantages to isometric rate control. First, *Isometric rate control produces smoother control trajectories.* By definition, with rate control the user has control of the velocity of the controlled object. Since the integrator in the rate control transfer function has a low pass filtering effect, the trajectories generated by isometric rate control therefore tend to be smoother than trajectories generated by isotonic position control. In many applications, this is particularly important. For instance, when controlling the entire graphics world, or moving the virtual camera in 3D graphics, we need the control motion to be as smooth as possible. Another advantage related to rate control is the fact that control motions are not restricted by hand anatomy. The magnitude of controlled movement is unlimited with rate control. With position control, the magnitude of controlled movement is limited by hand/arm length (in case of translation) and joint angles (in case of 3D rotation control devices). In order to reach a larger range of magnitude, one either has to increase the control gain (e.g. mouse for a large monitor), or relay or repeated clutching (lift mouse and reengage it at a new location). When space for position control device is limited, such as the case of a touchpad for portable computeres, many strokes of movement has to be made with position control device, reducing the overall performance of isotonic position input devices.

Given the desirability of rate control in many respects, it is therefore important to look into ways of improving isometric rate control. As discussed earlier, the key to rate control is the self-centering effect in isometric control. In the following section we compare performance of the same isometric rate control device with another device that is self-centering: a device which provides elastic resistance feedback.

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[12] Shumin: what “current study”? Perhaps should be reworded.

Analyses and Literature on Elastic versus Isometric Devices

A Preliminary Analysis

This section explores the differences between elastic rate controllers and isometric rate controllers. Since both isometric and elastic devices are self-centred, they both should be compatible with rate control, in light of the analysis and experimental results in the preceding chapter. The difference between the two is that the elastic device allows a certain extent of movement. Is the movement in an elastic device an advantage comparing to pure isometric (stiff) device? Do isometric and elastic devices afford a different "control feel" (Burrows, 1965)? It is clear (by definition) that the only control feel the human gets from an isometric device is force resistance. Also by definition, the user feels both force resistance and the displacement proportional to the force from an elastic device. The two variables (force and displacement) in an elastic controller co-vary (or even linearly co-vary if the springs used follow Hooke's law). This could imply that an elastic device gives a richer control feel than an isometric device, since the elastic device gives the same information in more than one form (force and displacement).

The Controversy Surrounding Isometric Versus Elastic Devices

Researchers have not had much agreement on the preceding hypothesis. Poulton, for example, firmly believes in the advantage of elastic devices: "Spring centring is the best kind of control loading", "... the man feels a pressure which is proportional to the distance of the control from its centre. The pressure cue augments the usual position cue, and help the man track more accurately" (Poulton, 1974, page 306). In practice, most commercial 2 DOF joysticks are elastic, but we do not know whether they have been constructed that way due to human performance considerations or due to manufacturing cost considerations. For the purpose of developing 6 DOF hand controller for teleoperation, McKinnon, King, and Runnings (1987) suggested that the controller should involve some displacement. They stated that pure isometric controllers may cause instabilities and over control, but this was concluded solely from their anecdotal observations; no formal study was reported.

Other researchers, such as Gibbs and Notterman, strongly believe in the advantages of isometric devices over elastic devices. As discussed earlier, Gibbs (1954) argued that "the discharge in some primary endings is considerably boosted in isometric conditions". Notterman further argued "When using the spring-loaded control, subjects had to learn to use feedback from the linearly related, theta-proportional reactive forces determined by Hooke's law, *conjointly* with movement cues and centrally stored information". In other words, Notterman considered the redundancy in elastic devices a burden to the human information processing system.

Many of the studies reviewed in our investigation of isometric devices in relation to isotonic devices are also relevant to the comparison of them to elastic devices. The following subsections review issues related to isometric and elastic devices in more depth, with emphasis on empirical studies investigating force versus movement with respect to proprioceptive cues.

Studies on Control Accuracy as a Function of Force and Movement and as a Function of Control Loading

Weiss (1954) reported a study on a positioning task without immediate visual feedback of cursor position (i.e. open-loop positioning). In one set of conditions, Weiss varied the maximum angular displacement of an elastic control stick from 3° to 30° while keeping the same pressure range from 1 to 30 lb. In another set of conditions the maximum pressure was varied from 0 to 30 lb. while keeping the same movement range (30°). He found that the relative positioning error and its variability decreased with the extent of movement but pressure variation had no effect on accuracy. He thus concluded that movement was the more crucial dimension than force in proprioceptive feedback. Unfortunately Weiss' study did not include a pure isometric condition for comparison.

Results contrary to Weiss' (1954) were reported by Bahrick, Bennett, and Fitts (1955). Bahrick and colleagues studied the accuracy of blindfolded subjects in positioning a 1 DOF horizontal rotary arm control as a function of spring loading. Subjects made rotary movements of 17.5°, 35°, and 70° with various starting torque and terminal torque conditions. They found that subjects had smaller relative errors when (a) amplitude of movement was larger, (b) terminal torque was larger, and (c) relative torque change per unit movement was larger. The positioning errors were smallest when the ratio of relative torque change to displacement was largest. In conclusion, Bahrick *et al* found that force could provide useful cues in movement control. This was contrary to Weiss' finding.

Briggs, Fitts, and Bahrick (1957) studied a compensatory tracking task of simulated aircraft dynamics (comprising simple integrators), with an elastic stick. Two levels of force and two levels of amplitude were tested in an experiment, with Time on Target (TOT) as performance measure. They found that "both force and amplitude (of movement) cues significantly affected performance, amplitude cues apparently exerting the greater influence". The best TOT measure was obtained with both sources at the largest extent. As with Weiss' study, a pure isometric condition was not tested by Briggs et al. (1957).

Notterman and Tufano (1980) did include both isometric and elastic conditions in a tracking task in position control mode. They found that the elastic controller was better than the isometric device in tracking predictable target motion and that the isometric device was better than the elastic device in tracking unpredictable target motion but these findings were true only in early learning stages.

Howland and Noble (1953) comparatively studied controls with no loading (isotonic), elastic loading, viscous loading, inertial loading and various combinations of them. No isometric controls were included in their study. Subjects were asked to track a horizontally moving bar driven by a 15 cycle per minute harmonic signal in position control mode. Ranked by percentage of time-on-target (TOT), subjects' performance with various loadings in decreasing order of TOT were: (1) elastic only, (2) elastic and viscous, (3) viscous only, (4) no loading (isotonic), (5) inertial only, viscous and inertial, elastic and viscous and inertial (not much difference among these three), (6) elastic and inertial. Howland and Noble attributed the superior performance with the elastic loading to two factors. (a) The elastic loading aids the reversals needed in harmonic movement. In other words, subjects may utilize the device dynamics in generating movement that coincides with the target signal (We return to this point in 3.1.5). (b) The feel of control handle position is augmented with elastic loading and therefore the "kinesthetic stimulation" is enhanced. This study is often cited in the literature on the effect of control loading. It should be noted, however, that the control handle in the study was rotary and the advantage of natural mapping in isotonic controls might not be well taken in rotary controls. However, the key conclusion that elastic controls augment position sense is agreed upon by many other researchers.

Psychophysical Findings on Force and Movement JND

Recently, psychophysical experiments have been conducted on human (finger) sensitivity in discriminating length and force. Durlach, Delhorne, Wong, Ko, Ranbinowitz, and Hollerbach (1989) and Tan, Pang, and Durlach (1992) found that human discrimination of length did not follow Weber's law[13]. The just noticeable difference (JND) was 8.1% for a reference length of 10 mm, 4.6% for 40 mm and 2.8% for 80 mm. In comparison, Pang, Tan, and Durlach (1991) and Tan et al. (1992) found that *force* JND did follow Weber's law. The average force JND was

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[13] Shumin: sorry, I'm uneducated. Can you add a footnote explaining Weber's Law?

around 7-8%, independent of reference force. It appeared that human sensitivity to force is lower than sensitivity to length, particularly for large ranges of length (>10 mm) or force (>2.5 Newton). For smaller ranges of force (<2.5 Newton) or length (<10 mm), the JNDs are about the same (See Figure 3 and 4 in Tan, et al. (1992)). One has to be cautious in applying these psychophysical studies to input control device design, however, since in these studies, the force JNDs were not obtained with isometric force.

Time Related Effects of Control Loading

The process of performing manual control tasks is not static. The dynamic properties of such tasks can not be overlooked, especially in rate control. Control loading is one factor affecting human judgement of these properties.

Adams and Creamer (1962) made the distinction between *regulatory* proprioceptive stimulation (RPS) and *anticipatory* proprioceptive stimulation (APS). RPS refers to the functions that proprioceptive feedback has on aiding users in judging their control actions. In addition to RPS, Adams and Creamer hypothesised that proprioceptive feedback might also aid users in anticipating the timing of their motor response (e.g. positioning a carriage along a trackway). Researchers found that control loading such as elastic springs indeed improve subjects' accuracy in estimating elapsed time. (Adams and Creamer, 1962; Ellis, Schmidt, and Wade, 1968; and Ellis, 1969). This is in agreement with Treisman's suggestion that subjects estimate time by "counting" external stimuli (Treisman, 1963).

The notion that the human may dynamically make use of proprioceptive cues provided by a control device is further demonstrated in Pew, Duffendack, and Fensch (1967). Pew and colleagues studied sine wave tracking with elastic controls in position control mode at various frequencies. With extended practice, subjects' performance was disproportionately better at certain critical frequencies. Furthermore, it was found that these critical frequencies changed with the elastic stiffness. This means that the subjects learned to use the natural resonant frequency of the arm-stick combination to match the frequency of the target movement being tracked.

The Neurophysiological Sources of Proprioception

Since proprioceptive feedback is one of the key issues in the debate on isometric versus elastic controllers, we now present a brief review of the basic literature on the mechanism of proprioception (or kinaesthesia).[14]

Neurophysiological research has found that a multiplicity of somatosensory receptors (mechanoreceptors) can be involved in providing information to the central nervous system (CNS) (Sage, 1977; Schmidt, 1988; Gandevia and Burke, 1992). Each type of receptor has its unique functions. The CNS integrates signals from these different types of receptors, producing an ensemble of somatosensory information.

Joint receptors. In early research, joint receptors were considered the most important source of proprioception. It was hypothesised that different groups of receptors at the same joint were tuned to particular joint angles; as a joint moved from one angle to another, different populations of receptors on the joint would be fired, much like how a mechanical-optical encoder works. Today's view, however, is that joint receptors are sensitive only when a joint approaches one of

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[14] For a more detailed coverage of the topic, the reader is refered to McCloskey (1978), Roland (1978), Clark and Horch (1986) or Matthews (1981).

the limits of its range (Clark and Horch 1986). As Matthews (1988) put it "Thirty years ago things looked relatively simple. The joint receptors were in, and everything else was out. ...This simplicity has now vanished; joint receptors are largely out and muscle receptors are in".

Muscle spindles. Muscle spindles are currently considered the major source of proprioception (Matthews, 1981, 1988). They are believed to be sensitive to both tension and movement, but more so to movement. Many studies suggest that "The muscle spindle receptors appear quite capable of encoding muscle length" (Clark and Horch, 1986).

Golgi tendon organs. According to early thinking, Golgi tendon organs were considered inaccurate protective measures, that is, they would signal only whenever the muscles approach their safe operation limits (Schmidt, 1988). Recent work, however, has found that they are actually very sensitive, but only to active tension, not passive tension (Jami, 1992). In fact they are considered as the major sensors of tension, although muscle spindles are also sensitive to tension. "Tendon organs, by nature of their response properties, appear the most likely candidates to signal forces" (Clark and Horch, 1986, page 13-55).

Cutaneous receptors. The bending of joints will stretch some regions of skin around the joints and relax others, causing the receptors in the skin to provide signals with regard to the position and movement. Experimental studies do not generally find an important role for cutaneous receptors in signalling positions, however, due to their slowly adapting nature. Anaesthesia of the skin around the knee joint had no effect on knee positioning, for example (Clark and Horch, 1986). However, this was not true of finger joints. The skin of the fingers might play a special role in proprioception (Clark and Horch, 1986).

In light of above, we can surmise what types of proprioceptors are approximately involved with each type of control devices. For example, when manipulating an isometric device, involving no movement and only tension, Golgi tendon organs should be the major source for proprioceptive feedback, although muscle spindles may also contribute to a lesser extent. With an isotonic device, where movement is involved but not tension, joint receptors, muscle spindles and cutaneous receptors in the skin around the joints might contribute to proprioception in varying degrees. When using an elastic device, on the other hand, both movement and tension are involved, and therefore joint receptors, muscle spindles and cutaneous receptors in the skin around the joints and Golgi tendon organs all may contribute to the proprioception of hand action. Collectively these hypotheses suggest, therefore, that all other factors being equal, an elastic controller should elicit response from more proprioceptors than any other class of device, because it allows movement while providing force feedback through the elastic elements.

The Role of Proprioception in Motor Control

Thus far we have reviewed issues related to proprioception in order to understand the difference between isometric controls and elastic controls. However, we have not addressed the question of how important proprioception is in motor control tasks in general. That is, to what extent does motor control rely on peripheral feedback, or, can most tasks be performed in an open-loop fashion with just centrally originated commands?

Motor behaviour accompanying our daily activities involves very complex coordination and regulation of joints and muscles, with a great number of degrees of freedom. Each hand alone has 17 active joints and 23 degrees of freedom, excluding the additional 6 degrees of freedom of the free motion of the palm. How such a complex system is controlled has interested many psychologists, physiologists, physical educators and human factors specialists. In general, two opposing views have been taken towards issues in motor control and have been the subject of a long-standing debate in the psychomotor literature (See Schmidt, 1988; Stelmach, 1979; and Singer, 1980 for general overviews). The centralist view emphasises the dominance of centrally stored motor programs and posits that human motor control comprises mainly open-loop behaviours. In contrast, the peripheralist theory stresses the importance of information feedback and posits that human motor control comprises mainly closed-loop behaviours. Both camps have found abundant evidence in support of their theories. The centralists have found cases which show that precise movement can be produced after deafferentation, either surgically with animals or accidentally with humans. Centralists also argue that proprioception is too slow for useful movement control. The peripheralists, on the other hand, have found much empirical counter-evidence to support their arguments against the centralist view. Although the debate is likely to continue, many other researchers suggest that the human motor control system actually operates under both modes, and that the role of feedback is a positive one in any case, even if central control is paramount.

Summary of the Reviews on Isometric and Elastic Devices

The foregoing reviews, as well as the related ones on isometric and isotonic devices, are by no means complete and exhaustive. Two facts are nonetheless apparent: (1) The human performance differences between isometric and elastic devices are a function of multiple factors and to understand these is much more complicated than one might expect. (2) The literature is controversial and definitive conclusions can not easily be drawn. Nevertheless, the analysis of the literature reveals the following major points.

1) Both isometric and elastic devices are self-centring and therefore compatible with rate control.

2) By definition, isometric devices operate on force alone while elastic devices involve both force and movement that are proportionally related.

3) Some researchers believe in the overall superiority of elastic devices (e.g. Poulton). Others (e.g. Gibbs, Notterman) consider isometric devices superior.

4) Human control accuracy increases with the amplitude of both movement and force, as evident in Bahrick et al (1955) and Briggs et al (1957). Weiss (1954), however, found that only movement contributes to control accuracy .

5) Displacement JND is smaller than force JND, that is, we are better able to perceive relative changes in position than changes in force.

6) Proprioception, as introduced by different types of control loading (e.g. elastic), may not only improve static control performance (accuracy) but also may improve dynamic aspects of control performance.

7) There are multiple neurophysiological sources of proprioception, some of which respond to force stimuli and others to movement stimuli. Elastic devices may elicit activation of more sources of proprioception.

8) Points 4 - 7 collectively suggest that elastic devices might be superior to isometric devices due to potentially richer proprioceptive feedback, however, the general role of proprioception in motor tasks is controversial. Different schools of thoughts put different degrees of emphasis on its importance in motor control.

A Two-Factor Theory

Based on the above review, we propose a two-factor theory for understanding the difference between isometric rate control and elastic rate control, illustrated in Figure 6. In contrast to isotonic or isometric devices which have fixed resistance (either zero or infinite), the resistance of elastic devices ranges between zero and infinity, depending on the stiffness of the elasticity. In light of the compatibility principle proposed in the previous chapter, a controller has to be self-centred in order to facilitate rate control processes. This self-centring effect decreases as the stiffness of the device decreases. When the elastic stiffness reaches zero, the elastic controller becomes a freely moving, isotonic controller without any self-centring effect. When the stiffness is infinite, on the other hand, the elastic controller becomes a non-moving, isometric device which has the strongest self-centring effect. In short, in order to maintain compatibility for rate control, the optimal stiffness for an elastic controller should be close to the infinite stiffness of an isometric device.

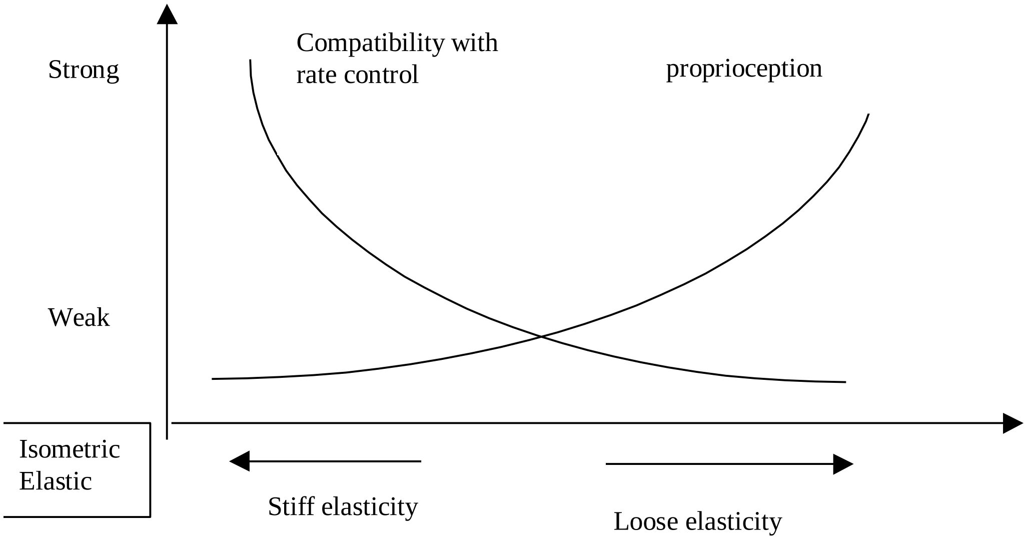

Figure 6: Illustration of two factor theory for elastic rate control devices: as the elasticity becomes increasingly loose (more movement), proprioception will be enhanced but compatability with rate control will decrease

In light of the analysis of proprioceptive feedback, on the other hand, a greater extent of displacement may allow the human operator to maintain a more accurate perception of control actions. For this reason, an elastic device should have a relatively low elastic stiffness to allow a greater extent of movement with the same range of force.

Apparently, these two factors, compatibility and feedback, dictate conflicting requirements for the magnitude of the elasticity. An optimal design will thus be a result of a trade-off between these two factors. It should be stiff enough so as to be compatible with rate control but loose enough to allow accurate proprioceptive feedback.

In light of such a two-factor theory, Zhai and colleagues (Zhai & Milgram 1993, Zhai & Milgram 1993b, Zhai 1995) compared an isometric 6 DOF rate control device (a Spaceball^{TM}) and a 6 DOF elastic rate control device with stiffness adjusted to accommodate both compatibility with rate control and proprioceptive feedback. Figure 7 and Figure 8 respectively show the performance differences between these two input devices in a 6 DOF docking task and a 6DOF tracking task. Results in both tasks demonstrate that the performance difference between the two input devices change with practice. The elastic rate control device appeared to be superior to the isometric rate device at the early learning stages, but such differences declined as the subjects gained more experience.

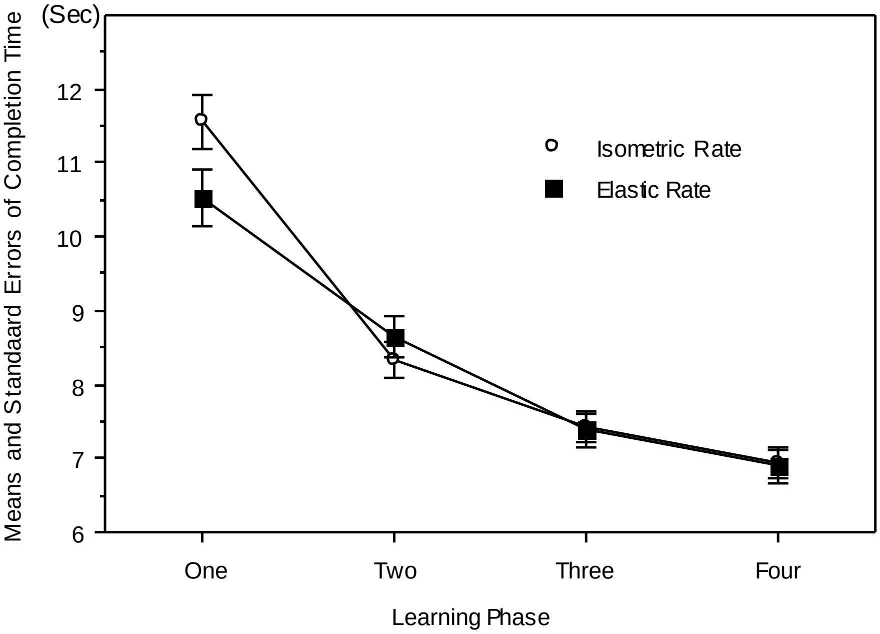

Figure 7: Elastic versus Isometric Rate Controllers in a 6 DOF Docking Task

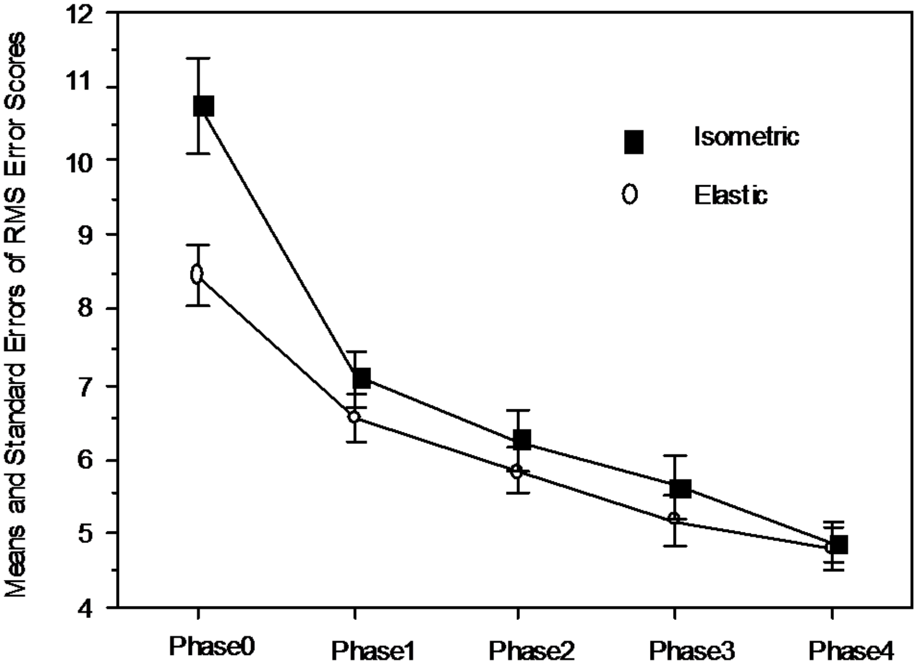

Figure 8: Elastic versus Isometric Rate Controllers in a 6 DOF tracking Task

This finding is in general agreement with some of the recent motor learning theories and empirical studies which represent a compromise between earlier more extreme centralist versus peripheralist views. One such example is the *schema theory* of motor behaviour (Schmidt, 1975, 1988), which states that the human motor control system comprises two types of schemata, *recall* and *recognition* schema, similar to the recall and recognition processes found in memory schema research. The recall schema, corresponding to central resources and information outflow, form the relationship between initial conditions, response specifications and response outcome. In contrast, the recognition schema, corresponding to feedback and information inflow, form the relationships among initial conditions, *sensory feedback* and response outcome. Both recall schema and recognition schema play important roles in motor movement. Their relative contribution depends on the pace of the task and the subjects' experience with the task.

Many researchers have demonstrated a shift from closed loop behaviour towards open loop human motor strategies, typically with decreasing importance of visual feedback, as learning progresses. In studying the organisational structure of human motor skills, Pew (1966), for example, found that motor skills were initially based on feedback but progress towards a hierarchical structure that is more centrally based. Pew reviewed many other motor control theorists' views and asserted: "The underlying themes of these proposals is the hierarchical nature of the control of skilled acts which develop with practice beginning with strict closed-loop control and reaching levels of highly automatized action with occasional 'executive' monitoring". Kohl and Shea (1992) recently replicated Pew (1966) and confirmed Pew's findings.

Based on tracking skill research, Krendel and McRuer (1960; also see Jagacinski and Hah, 1988 for a recent review) proposed their "*successive organisation of perception* (SOP)" theory. Krendel and McRuer identified three modes of tracking behaviour: error nulling, input reconstruction and precognitive behaviour. In the error nulling mode, subjects rely primarily on visual, exteroceptive information to minimise tracking error. In input reconstruction mode, subjects utilise additional proprioceptive information to form control actions. In precognitive mode, subjects depend on open-loop tracking patterns reproduced from memory, while exteroceptive and proprioceptive feedback become less important. With practice, in other words, subjects' behaviour progresses from the error nulling mode to the input reconstruction mode to the precognitive mode, while the source of information used shifts respectively from the visual exteroceptive to the proprioceptive and then to internal memory.

The results of the elastic versus isometric rate controllers experiments, discussed above, appear to support these theories and findings. In the early learning stage, when control behaviour was dominated by closed-loop inflow processes, the richer proprioceptive feedback from the elastic controller provided an advantage to the subjects in the elastic group relative to the subjects in the isometric group who had less rich proprioceptive feedback. As learning progressed, information feedback became less important and internal open loop mechanisms (motor programs) began to play a more important role, i.e., the motor control behaviour became more open-loop. Similar performance for the elastic and the isometric rate control conditions was therefore found in the later stages of the experiment.

The practical implications of the results can be interpreted a number of ways. First, the elastic rate control device is indeed a more advantageous device, in comparison with the isometric device. Second, with enough practice, performance with isometric devices can catch up with that of elastic devices but the time required might be much longer than indicated in the particular experimental task performed here (i.e. 20 to 40 minutes). In the experiment, subjects allocated full attention to the task and were coached thoroughly. In reality, especially in practical computer applications, where the users might not be trained *operators* as in aircraft piloting and teleoperation, users might take a longer time to reach stable performance with isometric devices. Third, equal performance does not mean equal *effort*, hence the differences between the two controllers may reappear when the user has higher workload or under stress conditions. In the progression-regression theory of human motor skills, Fuchs (1962) and Jagacinski and Hah (1988) suggest that when under stress, subjects may return to early behaviours. In the current context, users might therefore perform better with an elastic device when facing stress.

In summary, two factors play the most important roles in determining the differences between isometric and elastic devices: compatibility with rate control due to self-centring, and proprioceptive feedback. The literature suggests that an elastic device may provide richer proprioceptive feedback than an isometric device. The difference between an elastic device and an isometric device is not great with respect to performance, but rather with respect the ease of learning. Due to its richer proprioceptive feedback, an elastic device may be easier to learn than the corresponding isometric device. After sufficient practice, subjects' control behaviour may become more open-loop, with motor program based skills, and therefore the richer proprioception provided by the elastic device may no longer be a critical determinant of performance.

The Effects of muscle groups

The issue of relative performance of different muscle groups in manual control also has practical implications in the design of input devices. If some muscle groups or body parts are better at certain type of control manipulation, we should design input devices that encourage their use in those situations. The conventional ergonomic criterion in computer input device design, such a the shape of a mouse, is too often driven by comfort in holding it statically, rather performance efficiency when the device is dynamically operated.

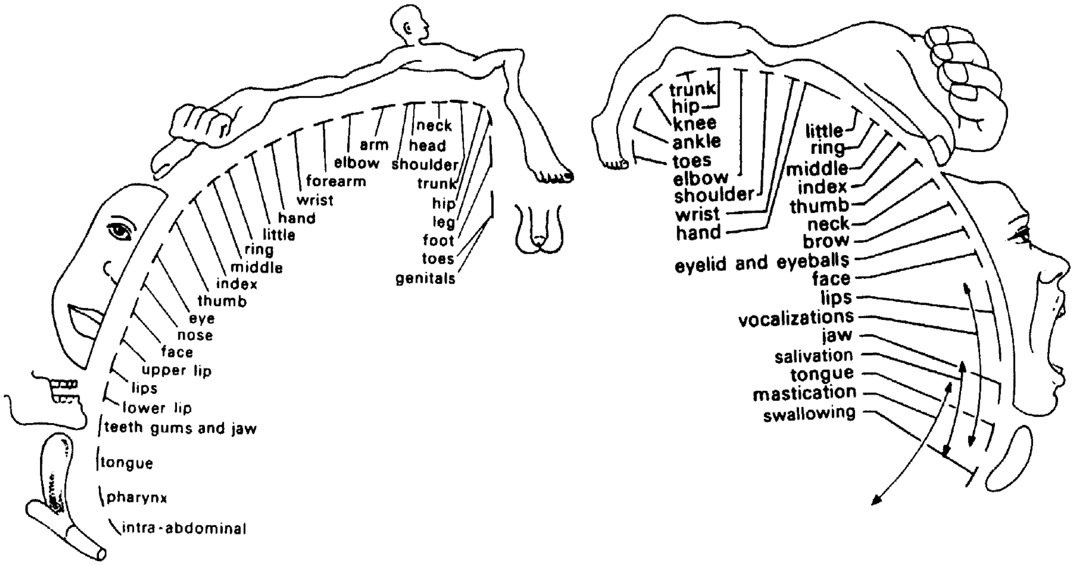

Figure 9: Homunculus model of the somatosensory (left) and motor (right) cortex, showing the mapping between different body parts and the brain (Adapted from Sage 1977).

Before we review the manual control literature on muscle group differences, let us first look at the neurophysiological aspects of different body parts. Studies have shown that various parts of the human body are represented in the brain disproportionately relative to their physical size and mass as illustrated in Figure 9, which illustrates the *Homunculus model* of the *somatosensory* (left) and *motor* (right) cortex. Note that the representations of the fingers and the hands in both the somatosensory and the motor cortex are much richer than those of the wrists, elbows and shoulders. The homunculus distribution of the cortexes suggests that a potential performance enhancement will result if fine muscle groups (i.e. fingers) are allowed to take part in handling an input device.

Gibbs again took the leading role in studying the effect of different body parts in manual control. In a one dimensional target acquisition task, Gibbs (1962) studied the effect of three different body parts: the thumb (activated by the carpometacarpal joint), the hand (activated by the wrist), and the forearm (activated by the elbow). He investigated each in both position and rate control systems with various control gains and time delays. Subjects' performance in Gibbs' study according to the ranking was: hand, forearm, and thumb.

Hammerton and Tickner (1966) later replicated Gibbs' study in a 2 DOF target acquisition task. Although Gibbs subsequently argued with Hammerton and Tickner about experimental methodology and credit ownership (Gibbs, 1967; Hammerton and Tickner, 1967), the two studies in fact arrived at a very similar conclusion, that performance with the hand (wrist movement) was superior to that of the thumb and the forearm. This advantage was greater in more difficult tasks such as those with long time delays (Hammerton and Tickner, 1966). Note that both studies found that the wrist was more effective than the thumb. Neither Gibbs nor Hammerton and Ticker included fingers in their studies, however.

The motor performance of different limbs has also been investigated in various Fitts' law.[15] These studies typically found the motor information processing rate (1/b) to be in the vicinity of 10 bits/second when the arm was involved in the movement. Fitts (1954) speculated that other limbs such as fingers might show different rates. Later studies supported this hypothesis. Langolf, Chaffin, and Foulke (1976) investigated the Fitts' law relationship using amplitudes of A = 0.25 cm, A = 1.27 cm and A > 5.08 cm. For the first two amplitudes, the experiment was carried out using a microscope. For the large range (>5.08 cm), the experiment was carried with direct vision. Langolf and colleagues observed that for A = 0.25 cm subjects moved the stylus tip (a 1.1 mm peg) primarily with finger flexion and extension. For A = 1.27 cm, flexion and extension of both wrist and fingers occurred. For A > 5.08 cm, the forearm and upper arm were involved in the movements. With this method of allocating actuation to different muscle groups by controlling the range of movement, Langolf and colleagues concluded that the information processing rates for the fingers, wrist, and arm were 38 bits/sec, 23 bits/sec and 10 bits/sec respectively (see Figure 6 in Langolf, et al., 1976). This study has been widely cited in the literature (e.g. Boff and Lincoln, 1988; Keele, 1986; Card, Mackinlay, and Robertson, 1991) as evidence that fingers are among the most dextrous organs.

Card et al. (1991) recently reviewed Fitts' law studies with various body parts (finger, wrist, arm, neck) and pointed out the limitations of the widely used computer input device - the mouse. They suggested "a promising direction for developing a device to beat the mouse by using the bandwidth of the fingers". Experimental work has not yet been produced to support this prediction, however.

In summary, both neurophysiological studies (the homunculus model) and Fitts' law studies suggest that use of the small muscle groups (fingers and thumbs) should result in better performance than the large muscle groups (arm and shoulder). However some studies in manual control (e.g. Gibbs, 1962; and Hammerton and Tickner, 1966) are not completely consistent with such a prediction.

Due to their theoretical motivation, most studies in the literature tend to compare performance of different muscle groups *against* each other. From a practical point of view, such a contrast is not necessary for the design of a 6 DOF input device. The human upper limb as a whole (from shoulder to finger tips) has evolved to be a highly dextrous and yet powerful device. Every part of it has its purpose and function. What is needed in input device design is to make use of all the parts according to their respective advantages. The larger muscle groups that operate the wrist, elbow, and shoulder have more power and a larger range of movement. The smaller muscle groups that operate the fingers and thumb have more dexterity. When all the parts work in synergy, movement range and dexterity can both be maximised. Zhai, Milgram and Buxton (1996) compared two 6 DOF input devices, both are isotonic position control devices. One the

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[15] See the previous chapter for an introduction and discussion of Fitts' Law.

devices, shaped like a tennis ball that could be easily manipulated with arm, hand and between fingers, consistently outperformed the other device that was mounted on a glove thus was only operated with the hand and arm.

Shumin: Can you consider adding:

1. some discussion of tapping tasks. My recollecton is accurate there are 2 issues here that are relevant: (1) that tapping speed is the one reliable predictor of aptitude for typing and (b)
2. 2. Add something on pragmatic vs epistemic action. Draw from GF's thesis (or perhaps we could et it from George directly). This could play into a factor outside of motor control, i.e., cognition, that should influence choice of device, i.e., depends on position sensitive devices. (Well, not quite – again, could have to do with SR compatibility).
3. A 2-3 paragraph of summary/conclusions to the overall chapter is needed to get closure.

4.