Visual control of stable and unstable loads: what is the feedback delay and extent of linear time-invariant control?

Ian D. Loram, Martin Lakie and Peter J. Gawthrop

1 Institute for Biomedical Research into Human Movement and Health, Manchester Metropolitan University, John Dalton Building, Oxford Road, Manchester M1 5GD, UK
2 Applied Physiology Research Group, School of Sport and Exercise Sciences, University of Birmingham, Birmingham B15 2TT, UK
3 Department of Mechanical Engineering, Centre for Systems and Control, University of Glasgow, Glasgow G12 8QQ, UK

Human balance is commonly described using linear-time-invariant (LTI) models. The feedback time delay determines the position of balance in the motor-control hierarchy. The extent of LTI control illuminates the automaticity of the control process. Using non-parametric analysis, we measured the feedback delay, extent of LTI control and visuo-motor transfer function in six randomly disturbed, visuo-manual compensatory tracking tasks analogous to standing with small mechanical perturbations and purely visual information. The delay depended primarily on load order (2nd: 220 ± 30 ms, 1st: 124 ± 20 ms), and secondarily on visual magnification (extent 2nd: 34 ms, 1st: 8 ms) and was unaffected by load stability. LTI control explained 1st order and stable loads relatively well. For unstable (85% passive stabilisation) 2nd order loads, LTI control accounted for 40% of manual output at 0.1 Hz decreasing below 10% as frequency increased through the important 1–3 Hz region where manual power and visuo-motor gain are high. Visual control of unstable 2nd order loads incurs substantial feedback delays and the control process will not be LTI. These features do not result from exclusive use of visual inputs because we found much shorter delays and a greater degree of LTI control when subjects visually controlled a 1st order load. Rather, these results suggest that delay and variability are inevitable when more flexible, intentional mechanisms are required to control 2nd order unstable loads. The high variability of quiet standing, and movement generally, may be indicative of flexible, variable delay, intentional mechanisms rather than the automatic LTI responses usually reported in response to large perturbations.

(Received 8 November 2008; accepted after revision 19 January 2009; first published online 26 January 2009)

Corresponding author I. D. Loram: Institute for Biomedical Research into Human Movement and Health, Manchester Metropolitan University, John Dalton Building, Oxford Road, Manchester M1 5GD, UK. Email: i.loram@mmu.ac.uk

Successful movement, balance and the manipulation of external objects requires the nervous system to control loads with very different mechanical properties. The fine positional control of stable and unstable loads is a demanding task which tests the sensory and control processes of the nervous system to their limits. For example, fine dissection, using visually enhanced sensory information, requires precise control of a stable massy load, namely the arm, hand, finger and instrument. Also, normal human standing requires the nervous system to exquisitely control a massy load which is passively unstable (Loram & Lakie, 2002a; Loram et al. 2005b, 2007a; Kiemel et al. 2006; van der Kooij & de Vlugt, 2007; Welch & Ting, 2008). In an approach designed to reduce the number of variables in real standing, pedal control of external unstable loads (Fitzpatrick et al. 1992, 1994, 1996; Fitzpatrick & McCloskey, 1994; Fukuoka et al. 2001; Loram et al. 2001; Nagata et al. 2001; Loram & Lakie, 2002b), manual control of loads of varying stability (Lakie et al. 2003; Loram et al. 2006; Chew et al. 2008), manual balance of one’s own body using a variety of sensory feedback modalities (Lakie & Loram, 2006) and manual, unstable stick balancing (Cabrera & Milton, 2002; Moss & Milton, 2003; Cabrera & Milton, 2004) have all been studied for the insight they provide into the neural control of standing balance.

Regarding the voluntary control of hand movements, ideas of the control process have shifted from peripheral ‘servo-mechanisms’ to the view that control is highly
adaptive, centrally driven and uses model based predictive processes (Neilson et al. 1988a; Wolpert et al. 1995; Gomi & Kawato, 1996; Miall & Wolpert, 1996; Miall, 1998; Miall & Jackson, 2006; Bays & Wolpert, 2007; Wolpert, 2007). By comparison, postural and balance research is more rooted in the servo-mechanism paradigm with the proportional-integral-derivative (PID) controller being particularly popular (Alexandrov et al. 2005; Maurer & Peterka, 2005; Lockhart & Ting, 2007; Welch & Ting, 2008). However, the physiological control mechanisms employed to balance unstable loads are uncertain. It is unclear whether or not predictive processes allow the nervous system to plan control activity on the basis of where the load is expected to be in the future (Fitzpatrick et al. 1996; Chew et al. 2008; Gawthrop et al. 2008), whether the control process is predominantly variable or predominantly time invariant (Alexandrov et al. 2005c, 2006; van der Kooij & de Vlugt, 2007), whether the control process is highly adaptive or relatively inflexible to changes in load properties (Chew et al. 2008) and whether the duration of central processing is long or short. These issues are important for resolving the neuro-physiological basis of balance in relation to the general control of movement.

Recent evidence has revealed similarities between voluntary manual control and normal standing. Ultrasound tracking has shown that the movements of the calf muscles in quiet standing are very similar to the hand movements of a subject manually balancing an equivalent body (Loram et al. 2005c) (online supplemental material) and to the intermittent manual adjustments during manual tracking. In all three cases the velocity power of these intermittent adjustments is in the range 1–3 Hz. These intermittent control adjustments have high variability and jerkiness and appear non-linearly related to the input (Stark & Navas, 1968; Miall et al. 1993). These facts strongly support the hypothesis that in both quiet standing and manual tracking a similar intermittent, low frequency process is responsible for the control output, i.e. muscle length and hand movement, respectively. Standing is essentially a compensatory tracking task: in compensatory tracking the subject has available only information about the state of the controlled load (position and velocity) and the control task is to minimise fluctuations in this state.

Peripheral, servo-mechanisms can drive muscle length at high frequencies up to 8 Hz (Rack et al. 1983) and this fact differentiates low frequency balance control from high bandwidth directly driven mechanisms. Quiet standing is characterised by low frequency drift and irregular oscillation associated with regulatory control of the human inverted pendulum (Kiernan et al. 2006). Experiments mimicking control of the human inverted pendulum have shown that the frequency of these intermittent adjustments in control output (calf muscle or hand) is not related to which sensory modalities are included or excluded: the source of information, proprioceptive, vestibular, or visual, appears to be irrelevant (Loram et al. 2005c; Lakie & Loram, 2006). In fact even the load stability appears to be irrelevant to the frequency of adjustments: the intermittent control output appears to be limited to a low mean frequency (~1 Hz) when the stability of the load is reduced to the limit where balance is unsustainable (Loram et al. 2006). This evidence suggests that a constant physiological constraint underlies central control of an unstable load in all these circumstances. This constraint was identified as being the upper frequency limit or bandwidth of the human balance control system (Loram et al. 2006).

Control theory tells us that the feedback time delay limits the bandwidth of any feedback control system (p 172, Skogestad & Postlethwaite, 1996). The rule of thumb is that the bandwidth (upper frequency limit in hertz) is given by $f_{bw} = 1/(2\pi\tau)$ where $\tau$ is the feedback time delay. If a random or unpredictable force is applied to the load, the feedback time delay is the duration for which there is no response from the control system. The time delay includes durations for transmission, processing and detection: it includes both the time taken for the force to move the load sufficiently that the load movement can be detected and also the time taken by the feedback system to construct and initiate the corrective response in the actuator.

Currently, there are at least two, partially conflicting, views of the balance process. One view, derived from stimulus–response analysis of disturbed standing, portrays balance as a simple feedback system, which is well described as a linear-time-invariant (LTI) process with a relatively short time delay, in which the feedback gains are altered according to the task and combination of sensory feedback (Peterka, 2002; Alexandrov et al. 2005; van der Kooij & van der Helm, 2005; Lockhart & Ting, 2007; van der Kooij & de Vlugt, 2007; Welch & Ting, 2008). A second view, derived from observations of human balance of inverted pendula and quiet standing, regards balance as essentially variable and poorly described as a linear-time-invariant process, with a longer time delay in which online processes of prediction, decision making and trajectory formation are involved (Morasso et al. 1999; Loram & Lakie, 2002b; Bottaro et al. 2005; Loram et al. 2005a,c, 2006; Lakie & Loram, 2006; Bottaro et al. 2008). According to the first view, if load properties are altered, feedback gain parameters (e.g. motor set) would be adapted, but there would be little if any change in feedback time delay. The second view predicts that altering the load might alter the processing required for trajectory formation and might be associated with significant changes in time delay.

Accordingly there are two crucial questions to resolve: firstly, what is the feedback delay and is it altered by load properties? Secondly, is the relationship between...
stimulus and response inherently variable, associated with longer latency processes, or highly time invariant, associated with short latency processes? Research into fine control of balance has largely ignored the significance and consequences of temporal variability between stimulus and response. As neural responses become longer in latency they also become temporally more variable. For example, the short latency stretch reflex has little temporal jitter of a few milliseconds (pp. 153–154 in Rothwell, 1994), functional stretch reflexes or triggered reactions have intermediate temporal jitter, and voluntarily intended reaction processes have much more temporal or phase variability (Chan et al. 1979 and Fig. 6.5, p. 118 in Brooks, 1986). A feedback delay of high variability is more consistent with control processes that are slower, higher level and more 'intentional'.

For the balance of external unstable loads, studied generally and in relation to human standing (Fitzpatrick et al. 1992, 1996; Loram et al. 2001, 2006; Cabrera & Milton, 2002, 2004; Loram & Lakie, 2002b; Lakie et al. 2003; Chew et al. 2008), there is no accurately known value of the feedback time delay. When participants balance an external unstable load using visual feedback, existing estimates indicate a delay of 400–500 ms (McRuer & Jex, 1967; p. 398 in Wickens & Hollands, 2002). However, more accurate measurements are possible today and it is unclear whether these previous values include system lag due to the biomechanics of the load, muscles and limbs as well as the feedback time delay. Moreover, the extent of linear-time-invariant control, and its frequency analysis, for example with respect to the important 1–3 Hz range, has not been characterised.

A methodology is needed to determine accurate values of the feedback time delay and measure the extent of time-invariant processes in the control of unstable loads. Ideally, the task would be similar to quiet standing. Quiet standing requires regulation of an inverted pendulum, and that part of balance can be reduced to a compensatory tracking task. Here we replicated that demand in a set-up, which specifically excludes all vestibular and proprioceptive feedback. In this set-up, the load is equivalent to the human inverted pendulum (Loram et al. 1992; Lakie et al. 2003; Lakie & Loram, 2006). The passive stabilisation of the load by a spring is equivalent to that provided by intrinsic ankle stiffness determined mainly by the Achilles tendon. For small sways, that intrinsic stiffness is approximately 85% relative to the gravitational load stiffness of the inverted pendulum (Loram & Lakie, 2002a; Casadio et al. 2005; Loram et al. 2005b, 2007a). The participant controls the inverted pendulum by moving one end of the spring, which is analogous to lengthening and shortening the muscles in the active agonist muscle–tendon unit which is soleus–gastrocnemius during quiet standing. Previously the load has been a real pendulum which on various occasions has been controlled by the calf muscles similarly to standing (Loram et al. 2001, 2006; Loram & Lakie, 2002b) and manually by a spring (Lakie et al. 2003; Lakie & Loram, 2006). On this occasion the pendulum and spring was implemented virtually in real time. A manual joystick was used to move the virtual spring and the pendulum position was displayed on an oscilloscope: we have previously demonstrated the equivalence of (1) using a joystick vs. manually holding a spring and (2) viewing the motion via an oscilloscope vs. whole visual field motion as the person actually sways (Lakie & Loram, 2006).

In this current formulation, the set-up replicates the core demand of standing balance and is equivalent to a compensatory, manual tracking task. This has major advantages. First, drawing on our existing investigations, we can explicitly explore the relationship between balance and manual tracking. Second, we can alter the load completely and explore more fully whether the (1–3 Hz) intermittent human control output is intrinsic or whether it is task and load related. For example, we can remove property of mass from the load, (convert the 2nd order load to a 1st order load). This produces a load which is less complex to control.

We investigated the effect of load order (1st, 2nd), stability (100–20% passive stiffness) and visual magnification (threshold) on the feedback time delay. A disturbance was added to the manual output and, without assuming any particular model, we used non-parametric analysis to measure the feedback delay, extent of linear-time invariant (LTI) control and the visuo-motor transfer function. We address the following specific questions.

1. What is the time delay? And is this delay primarily determined by (a) the order of the system (1st or 2nd i.e. containing mass), (b) the stability of the system (passive stiffness 100% – 20%), or (c) the visual size of movement (threshold)?

2. What is the extent and frequency distribution of linear time invariant control?

3. How does the visuo-manual control of 2nd and 1st order loads relate to human automatic or intentional control processes?

4. What insight can control of 2nd or 1st order loads shed on regulation of quiet standing?

**Methods**

**Ethical approval**

These experiments were approved by the safety and ethics subcommittee of the School of Sport and Exercise Sciences, University of Birmingham. Participants gave informed consent to these experiments which conformed to the
standards set by the latest revision of the *Declaration of Helsinki*.

**Procedure**

Eleven healthy adults, 9 male and 2 female, aged 20 to 56 years (33 ± 13 years, mean ± S.D.), sat quietly in a self selected position. Participants controlled a real-time virtual load using a sensitive joystick which was supported on a table in front of them (Fig. 1). Participants observed load position on an oscilloscope of full scale range 23 cm placed 160 cm away. Six loads (combinations of load and oscilloscope magnification) were presented in randomly selected order and participants were asked to balance each load for one trial of 205 s. Participants were instructed to keep the load position near the centre of the oscilloscope and were told that deviation from the centre was the measure of performance. Since the task required close, continuous attention, a mental break of up to 5 min was offered between trials.

Previous to the experiment, all participants were given an opportunity to familiarise themselves with the task and gain confidence in their ability to balance the different loads within the limits imposed by the oscilloscope display. The familiarisation included an explanation of the effect of the joystick on the load. Participants were told that for 1st order loads, the position of the joystick specified the velocity of the load and that for 2nd order loads the position of the joystick modulated the acceleration of the load. They were also told to locate the neutral position of the joystick, which applied no effect on the load. The purpose of the explanation was to speed up the familiarisation and enable any knowledge based predictive processes which might be utilised during the task. All subjects were able to perform the task for all loads within a few minutes of practice and thereafter improved increasingly slowly, if at all within the time scale of the session. If the load was occasionally dropped and passed beyond the positional limits of ±10 V, the load position was returned to the centre with zero velocity within a few tenths of a second. Two participants were veteran inverted pendulum balancers, two had limited previous experience, and seven had no previous experience of this task.

**Apparatus and measurements**

The real-time virtual loads were constructed using Simulink, were compiled using Real-Time Workshop and executed on a laptop using Real-Time Windows Target within MATLAB v7 (all from The MathWorks, Natick, MA, USA) at a sample rate of 1000 samples per second which gives essentially continuous-time behaviour.

The loads (Table 1, Appendix) were based on an inverted pendulum model of a standing human balanced by a single contractile element (calf muscles) acting through a compliant tendon (Lakie et al. 2003; Loram et al. 2005b,c). The load stiffness (gravitational toppling torque per unit angle) (Fitzpatrick et al. 1992), mgh, was based on a typical mass, m of 70 kg, gravitational acceleration g of 9.81 m s\(^{-2}\), and a centre of mass height, h of 0.92 m giving 632 N rad\(^{-1}\).

![Figure 1. Visually guided manual control of stable and unstable loads](image-url)

Participants sat at a table, manipulating a table supported, sensitive uni-axis, joystick with their self chosen hand. Joystick voltage and a continuous white noise disturbance were sampled digitally and applied to a virtual load running in real time in Simulink\(^{\circledR}\). Position of the load was displayed 160 cm away on an oscilloscope (CRO) of full scale range 23 cm and subjects were instructed to maintain a central position as closely as possible. Six virtual loads of varying order, stability and oscilloscope magnification were controlled (Table 1). Loads were derived from a simple muscle–tendon inverted pendulum model of human standing (Appendix A) where joystick position is analogous to changes in contractile element length and the load has the dynamical properties of a standing adult. To manipulate the frequency bandwidth required to control the load, stability was varied from perfectly stable (equivalent to a mass), to normal standing stability, to reduced stability. To manipulate the complexity of the required human feedback control, load order was varied from 2nd to 1st. To manipulate the duration before which load movement was detected, oscilloscope magnification was varied from a convenient normal and sensitive setting (6 cm V\(^{-1}\)) to one 10 times higher in which barely perceptible movements would be easily perceptible and where load movement had to be constrained within closer limits.

© 2009 The Authors. Journal compilation © 2009 The Physiological Society
We altered the degree of passive stabilisation by altering the stiffness of the virtual tendon giving values of 100%, 85% and 20%. For an unstable load such as an inverted pendulum, the time constant specifies the exponential growth rate of load position through time if no control is applied to the joystick and is calculated from the ‘poles’ or eigenvalues of the load transfer function denominator (Appendix). The 85% tendon gives an unstable, ‘inverted pendulum’ load with a time constant of 0.92 s equivalent to that experienced by an adult during normal standing. The 20% inverted pendulum load, is more unstable than the 85% pendulum and has a time constant of 0.39 s equivalent to that experienced by someone standing on a moving platform such that their ankle rotations are beyond the range of their short range passive stiffness (Loram et al. 2007a,b). The 100% tendon converts the unstable ‘inverted pendulum’ load into a stable load with a time constant of 0.92 s equivalent to that experienced by someone standing on a moving platform such that their ankle rotations are beyond the range of their short range passive stiffness (Loram & Lakie, 2002; Casadio et al. 2005; Loram et al. 2005b,c, 2007a). Consistent with measured values, a passive ankle viscosity of 2.9 N m rad⁻¹ s was also included (Loram & Lakie, 2002a). The transfer functions for this load and the modified loads are derived in Appendix and summarised in Table 1. This experiment represents a logical progression from previous experiments in which participants balanced a real external load using only visual feedback (Lakie & Loram, 2006; Loram et al. 2006).

We wanted to know whether the feedback time delay was dependent on the properties of the load such as the existence of mass, the degree of passive stabilisation and the extent to which movement of the load is visible.

We altered the extent to which movement was visible by increasing the magnification on the oscilloscope by a factor of 10 from 6 cm V⁻¹ to 60 cm V⁻¹.

We altered the degree of passive stabilisation by altering the stiffness of the virtual tendon giving values of 100%, 85% and 20%. For an unstable load such as an inverted pendulum, the time constant specifies the exponential growth rate of load position through time if no control is applied to the joystick and is calculated from the ‘poles’ or eigenvalues of the load transfer function denominator (Appendix). The 85% tendon gives an unstable, ‘inverted pendulum’ load with a time constant of 0.92 s equivalent to that experienced by an adult during normal standing. The 20% inverted pendulum load, is more unstable than the 85% pendulum and has a time constant of 0.39 s equivalent to that experienced by someone standing on a moving platform such that their ankle rotations are beyond the range of their short range passive stiffness (Loram et al. 2007a,b). The 100% tendon converts the unstable ‘inverted pendulum’ load into a stable load with a time constant of infinite duration. This load can be thought of as simply being a ‘mass’ with no destabilising effect from gravity. For all the second order loads, the position of the joystick modulates the acceleration of the load in addition to the destabilising effect of gravity, which is moderated by the passive stiffness of the tendon.

We removed the mass content of the load by reducing the 2nd order load to a 1st order load. For this load, the position of the joystick specifies the velocity, and the load is stable with no destabilising effect due to gravity.

The participant operated a hand held contactless single axis joystick (HFX Magnetic, CH Products Ltd, Vista, CA, USA) with internal restoring spring removed. The joystick voltage was applied to the virtual load and offset so that that the central position of the joystick applied a small virtual force to the load. Movement of the load exerted no influence on the joystick and the only information regarding load movement was available visually from the oscilloscope. By comparison with standing, this is analogous to balancing an equivalent load (Fitzpatrick et al. 1992; Loram & Lakie, 2002b) with no proprioceptive or vestibular information regarding load movement or force applied to the load. The participant did know the position of the joystick: this information is analogous to knowing the length of the calf muscles during the paradoxical muscle movements of quiet standing (Lakie et al. 2003; Lakie & Loram, 2006). For all loads we kept constant the relationship between joystick movement and virtual force applied to the loads: this is reflected in the fact that the denominator of the transfer function is the same for every load (Table 1). Control of the load requires the participant to make continual forward and backward adjustments of the joystick typically involving the flexors of the fingers and adductors of the thumb. The joystick gain was 2.5 mm V⁻¹, and thus the control movements of the joystick were small (∼1–3 mm).

To reveal the feedback time delay it is necessary to apply an unpredictable stimulus to the closed loop human-load system and measure the loop delay between the stimulus and the corrective response. Unlike machines, with human subjects it is impossible to achieve an unpredictable stimulus because humans are prepared for the stimulus and rapidly learn at least the statistical properties of the stimulus such as the mean value and spread which reduces the delay (p. 121 of Poulton, 1974; Neilson et al. 1988b). We did not add the disturbance to the movement displayed.
on the screen (output disturbance), because humans easily perceive and filter out or are distracted by the artificial higher frequency components of the stimulus (p. 211 of Poulton, 1974); thus we added the continuous disturbance stimulus to the joystick signal (motor disturbance) and measured the mean delay between the stimulus and the corrective movement of the joystick. We added a band-limited, gaussian, white noise stimulus to the joystick voltage: the virtual force applied to the load was the sum of the joystick and disturbance signals (Fig. 1). The disturbance was band-limited to avoid aliasing artefacts introduced by the sampling process and was chosen to have a uniform spectrum in the range 0.01–10 Hz (with no or very limited power outside this range). The upper limit was chosen to be well above any possible human control bandwidth; the lower limit was chosen to avoid leakage effects due to the limited time span (200 s) of the data. Preliminary experiments showed that coherence between the disturbance and joystick was greatest when the participants were able to maintain close control of the load. The disturbance amplitude was constant for all subjects and set to allow sustained control of the unstable loads.

All three signals, load position, joystick position and applied disturbance (Fig. 2), were sampled at 100 Hz and recorded to 16 bit resolution using a separate, second data-logging computer. The Nyquist sampling frequency corresponding to the disturbance cut-off frequency of 10 Hz is 20 Hz. The sample rate (100 Hz) was chosen to be five times this value so that an anti-aliasing filter could be used to resample the data to a lower sample rate thus removing any aliasing artefacts from frequencies above 10 Hz arising from non-linear effects.

Non-parametric data analysis

For each trial, non-parametric frequency analysis (Fig. 3A–C) was used to calculate the following quantities:

1. power spectra of the disturbance, $P_{dd}$, load position, $P_{yy}$, and joystick position, $P_{uu}$, where $d$, $y$ and $u$ represent the disturbance, output (load position) and control signal (joystick position) of the closed loop system (Fig. 1).
2. bivariate coherences between disturbance and output, $\gamma_{yy}^2$, and disturbance and joystick position, $\gamma_{dy}^2$, respectively.

We used Welch’s averaged, periodogram method with a Hanning window and non-overlapping segments of duration of 10.12 s (Halliday et al. 1995).

For each trial, the unbiased cross correlation, multiplied by the sampling frequency, was calculated between disturbance and load position, $r_{dy}$, and joystick position, $r_{du}$, respectively. This measures the statistical association between the disturbance and the two quantities at different time lags, and, because the disturbance approximates white noise, it provides a non-parametric estimate of the closed loop impulse response functions between disturbance and load position, and joystick position, respectively.

Causal, ‘non-parametric’, linear time invariant analysis

While making minimal assumptions, we analysed the closed loop response to the disturbance as a causal, linear-time-invariant (LTI) process. As assumptions about the human controller affect the estimate of the time delay, a key feature of this paper is to base time delay estimation on non-parametric models derived from the data. Such models are typically either impulse response or frequency response models (p 168, Ljung, 1999). Unfortunately, estimating such models directly leads to poorer estimation properties. It is therefore better to identify high-order parametric models. Thus, the closed loop relationships between disturbance and load position, and disturbance and joystick position, respectively, were both modelled as an auto regressive moving average (ARMA) process

$$y(t) + a_1 y(t-1) + \ldots + a_n y(t-n) = b_1 d(t-n_k) + \ldots + b_n d(t-n_k-n+1) + e(t)$$

where $y(t)$ is the position of the load (or joystick respectively) at time sample $t$, $d(t-n_k)$ is the disturbance at time sample $t$ delayed by $n_k$ time samples, $e(t)$ is a random ‘white noise’ input from a gaussian distribution of mean value zero and constant standard deviation. The coefficients $a_{1..n}$ and $b_{1..n}$ are respectively the auto-regressive and moving average coefficients of this generalised linear process: the auto-regressive coefficients define the response of the process to a stationary white noise input: the moving average coefficients and the delay determine the coupling between the disturbance and the stationary process, and in combination with the autoregressive coefficients define the impulse and frequency response functions between disturbance $d$ and output $y$. Thus the ARMA process produces a LTI model which relates the response variable load (or joystick) position to the preceding random ‘white noise’ input, and to the preceding history of load (or joystick) position. The remnant is that variation in load (or joystick) position that is not captured by the LTI model. The parameters of such models are not meaningful as such but rather can be used to derive the required non-parametric models in the time or the frequency domain. When the number of coefficients $n$ is large, no particular structure of controller is implied and the model is effectively non-parametric. The salient difference between this analysis and the preceding non-parametric analysis is that the ARMA
process models only that response which is causally related to the disturbance whereas the cross correlation analysis includes the remnant which is not causally related to the disturbance.

**Validation.** We used three accepted validation procedures to check the credibility of ARMA models (MATLAB System identification toolbox documentation and Ljung, 1999). First we compared the non-parametric analysis with the equivalent ARMA results. The non-parametric coherence is compared with extent of LTI power (see below and Fig. 4). The non-parametric cross correlation is compared with the LTI impulse response function (see below and Fig. 5). Second, for the duration of the feedback time delay (see below) we compared the LTI closed loop, disturbance to load, impulse response function with the known open loop impulse response of the load. Third we tested whether the prediction errors (residuals) of the ARMA models are independent of each other and of the disturbance using the ‘independence’ and ‘whiteness’ tests.

**Selection of sampling interval.** The validation procedures were used to select the sampling interval of the ARMA models. For the models relating disturbance to joystick a 30 ms interval was optimal with 40 ms in a few cases. For the models relating disturbance to the first order load, a 10 ms interval was necessary. For the disturbance to 2nd order load, a 20 ms interval was necessary. We used an anti-aliasing (low-pass), linear phase FIR filter (with approximately unity gain up to the re-sampling frequency and cut-off at the mid frequency between the re-sampling and original sampling frequencies) to down sample the signals.

**Selection of model order.** To prevent over-fitting, the model order or number of coefficients, \( n \), and also the number of delays was selected using the Akaike (AIC) information criterion. By comparison with other criteria such as the Bayesian Information Criterion, this criterion prioritises the highest explanation of the data with a higher number of coefficients (p. 329 of Pintelon & Schoukens, 2001), which is more suitable for a ‘non-parametric’ analysis. For the 2nd order loads, the model order numbers (mean ± s.d.) were 22 ± 10 and 49 ± 15 for the disturbance to load and joystick functions, respectively. The corresponding values for the 1st order loads were 109 ± 1 and 73 ± 5. All the disturbance to joystick and 60 out of 66 of the disturbance to load ARMA models complied with validation tests. In the remaining six disturbance-load models the violations were very marginal, so the models were included in the analysis. The averaged comparison results of the first two validation tests are shown in Figs 5 and 6.

**Quantities calculated from the models.** From the ARMA models relating disturbance to load (\( dy \)) and joystick position (\( du \)) respectively, we calculated:

1. the closed loop impulse response functions \( g_{dy} \) and \( g_{du} \) (Fig. 3D,E),
2. the open loop, visuo-manual transfer function of the human controller \( C_{nu} \). \( C_{nu} \) is complex and represents the mean transformation (gain and phase) between load position (volts) displayed on the oscilloscope and joystick position (volts). We took advantage of the fact that the load transfer function \( P \) is known precisely and following standard textbook practice (Skogestad & Postlethwaite, 1996) we calculated first the complementary sensitivity function \( T = -G_{du} \), where \( G_{du} \) is the closed loop transfer function relating the disturbance to joystick position, and then the loop gain \( L = T/(1 - T) \) and the controller \( C_{nu} = L/P \).
3. the LTI responses \( Y(t) \) of the models to the known disturbance but with no random input using:

\[
Y(t) + a_1 Y(t - 1) + \ldots + a_n Y(t - n) = b_1 d(t - n_k) + \ldots + b_{nk} d(t - n_k - n + 1)
\]

4. the remnant \( E(t) = Y(t) - y(t) \) which is the difference between the model response \( Y(t) \) and the original load or joystick time series \( y(t) \).
5. the frequency power spectra of the model responses \( P_{YY} \), remnants, \( P_{EE} \) and respective load and joystick signals \( P_{Yy} \).
6. the power contained in the linear time invariant process \( P_{YY} \) as a proportion \( R \) of the total power (remnant plus original time series), where \( R \) is a function of frequency given by:

\[
R = P_{YY}/(P_{EE} + P_{Yy})
\]

**Calculation of feedback time delay**

We calculated the feedback time delay from the closed loop impulse response function \( g_{du} \) relating disturbance to joystick (Fig. 3E–F) and also the cross correlation function \( r_{du} \). The response between time zero and the first minimum (Fig. 3F) was least squares fitted as a constant followed by a straight line: the time delay was calculated from the intersection of the straight line with the time axis. This method was chosen on account of its temporal resolution, robustness and consistency. The method was tested on predictive control models (Gawthrop et al. 2008) tuned to the human IRF \( g_{du} \) and with a range of known delays between 0.01 and 0.35 s: using model simulation data and the ARMA analysis, the method estimated the time delay with an error (overestimate) of 9 ± 5 ms (mean ± s.d.).
Statistical analysis

Following data analysis, the main measures of interest for group analysis were the feedback time delay, and the power, coherence, complex transfer and impulse response functions. The feedback time delays were tested for differences according to load order and oscilloscope magnification using a two way ANOVA and were tested for differences according to load stability using a one way ANOVA. For the other functions, the mean and 95% confidence values were calculated for each load. For selected frequency ranges, the mean values were tested for differences between loads using one way ANOVA.

Generally, unless stated otherwise, individual values are quoted as a mean ± standard deviation.

Results

Although there was variation in ability, all subjects managed to balance all loads with a small amount of familiarisation. One subject dropped the more unstable loads several times. Subjects learnt to maintain a light, sensitive touch often with one finger and a thumb rather than a grasp with the hand. The most challenging loads were the 20% unstable load and the 85% unstable load with high visual gain. When the loads were randomly changed from one trial to another, the participant’s initial efforts were both illuminating and often amusing. Initially, their control would be inappropriate reflecting that of the previous load. They would either furiously overcorrect or would be frustratingly sluggish in their response. Within seconds or tens of seconds they would realise what was wrong, and would apparently ‘snap in’ to a previously learned appropriate mode of control.

Representative behaviour balancing an unstable load

Figure 2 shows a representative subject balancing the basic load, the 85% unstable load (‘muscle-tendon inverted pendulum’) with an oscilloscope gain of 6 cm V\(^{-1}\). The movements of the unstable load are smooth and small (a few centimetres on the oscilloscope) (Fig. 2A). The LTI model captures higher frequency load movements well but captures lower frequency load movements less well. This experimental arrangement provides a very precise record of motor output (joystick) (Fig. 2B), which is more complete than the EMG or contractile length that can be recorded during normal standing (Loram et al. 2005b). The joystick movements are small (2.5 mm V\(^{-1}\)) and have higher frequency content than the load. There are abrupt, non-linear changes in joystick position (e.g. 8 s, 10 s). The LTI model captures the lower frequency movements of the joystick quite well although there is a remnant error at very low frequency. The LTI model captures the higher frequency joystick movements badly: the LTI model is too smooth and cannot capture the intermittent abrupt changes. The disturbance (Fig. 2C and D) is substantial in size relative to joystick movements and has higher frequency content which is random up to 10 Hz.

For the representative subject, the power, coherence and ARMA derived impulse response functions are shown in Fig. 3.

The disturbance has uniform power up to 10 Hz, which approximates white noise (Fig. 3A). Load power decreases markedly with frequency on account of the inertia of the system. Joystick power is substantially higher than load
beyond 0.5 Hz reflecting the human controller’s derivative action required to stabilise this system. The measurements of load and joystick have an excellent frequency response with neither load nor joystick reaching measurement noise levels within the 10 Hz frequency range.

Coherence measures the extent to which one signal is linearly related to another. Linearly related means a constant gain and a constant phase relationship between the two signals. The coherence between disturbance and load position (Fig. 3B) is high beyond 4 Hz: at these frequencies the subject exercises little influence on the response of the load to the disturbance and so the relationship is effectively open loop (uninfluenced by human feedback). The coherence decreases above 7–8 Hz, reflecting a possible effect of hand tremor influencing load movement in addition to and unrelated to the disturbance.

Figure 3. Representative power, coherence and impulse response analysis
For the representative trial is shown the following: A, power of the disturbance (horizontal dashed), load (continuous line) and joystick (dashed line); B, coherence between disturbance and load; C, coherence between disturbance and joystick; D and E, closed loop impulse response functions between disturbance and load and joystick respectively. Dashed lines show 95% confidence intervals (A–C) and 2 S.D. intervals (D–E). The frequency invariant 95% confidence level is also shown horizontally in B and C. The inclined straight line in D shows the open loop response of the load to an impulse. The vertical line in E shows the estimated time delay. F, estimation of time delay from the impulse response function (IRF). The feedback time delay is shown in the expanded IRF between disturbance and joystick from Fig. 3E as the time before any movement occurs. The estimation method included fitting a constant and straight line and calculating the intercept with the time axis. This provided a robust consistent method, insensitive to noise and remnant in the IRF, and possibly overestimated the delay by approximately 9 ms.
Figure 4. Power, coherence and proportion of LTI response for all loads
All curves show variation of the quantities with frequency, for each load, averaged over 11 trials (one trial for each subject). Dashed lines show 95% confidence intervals in the mean. Left and right columns represent the load and joystick, respectively. A and B show power with the disturbance power shown additionally (horizontal curves) in A. C and D show coherence between disturbance and load and joystick, respectively. E and F show the proportion of LTI response for disturbance to load and joystick, respectively. Horizontal lines in C and D show the 95% confidence intervals.
Below 2 Hz, the coherence is low. At these frequencies the load is influenced by joystick movement as well as the disturbance; variability in the human feedback means the load response to disturbance is not predictable with accuracy. There is a dip in coherence between 1 and 2 Hz indicating that the variable human influence is relatively high at these frequencies.

Coherence between the disturbance and joystick position (Fig. 3C) is low generally; this means that the human feedback control of the joystick is not well predicted by the disturbance. Since measurement noise of the recording apparatus is low, this means the human response is variable. Note this coherence was representative of all subjects and this subject was experienced and able at balancing the load. Beyond 3 Hz the coherence is very low indicating little predictable feedback control.

The closed loop impulse response function (IRF) between disturbance and load position (Fig. 3D) shows little deviation from open loop behaviour for 0.48 s remaining within the ±2 S.D. confidence intervals. Thereafter, damped oscillation with a settling time of more than 5 s demonstrates that balance is successfully sustained and the closed loop system (incorporating human feedback) is stable.

The closed loop IRF between disturbance and joystick (Fig. 3E) shows a delay of 0.23 s; statistically, there is no response for this duration so the system is open loop with respect to unpredicted disturbances for 0.23 s. Since there is no joystick movement, this dead time is associated with detection thresholds, processing and neural transmission. There is a further 0.25 s before the joystick reaches the peak response. Thus there is an effective delay of 0.48 s before feedback control activity has a substantial effect on the load. This latter 0.25 s is associated with low pass dynamics of the load, muscle, hand and joystick in addition to detection thresholds, neural processing and transmission. The subsequent damped oscillation is associated with stabilizing feedback control of the load.

Close examination of the disturbance to joystick IRF in Fig. 3F shows that the delay is a least seven samples (0.21 s) and less than eight samples (0.24 s). The estimate derived from fitting a straight line (0.229 s) lies within this range and illustrates the uncertainty of the estimate which is approximately ±10 ms. This method of estimating delays proved to be robust, consistent and reliable; whereas estimating delays from the number of delays in the ARMA model was not reliable because sometimes the initial values of the IRF oscillated about zero with small, non-significant values before deviating strongly for the main peak.

Summary of all subjects controlling all loads

Figure 4 shows a frequency analysis of the power, coherence and proportion of LTI control for all loads.

The same 'white noise' disturbance was given for all loads and all subjects (Fig. 5A). As shown by the representative subject, load power decreases with frequency according to the low pass filtering of the load (Fig. 4A). First order loads have higher power than 2nd order beyond 0.4 Hz: they have no 'mass' to absorb the disturbance and so transmit more power of the disturbance at higher frequencies. The low stability (20%) and high visual gain 2nd order loads were difficult to control reflected by more load movement and power than the 100% and 85% cases. For the high visual gain 2nd order load, the load movements seen by the participant are 10 times larger than the actual movements shown in the power spectra. Thus between 0.7 and 10 Hz, the observed load movement has similar power to the 1st order load (Fig. 4A green vs. yellow). Joystick power (Fig. 4B) is greater than load power at higher frequencies reflecting sensitivity to higher derivatives of load movement and impulsive, intermittent action. Generally, there is more joystick movement associated with 2nd rather than 1st order, high rather than low magnification and with low rather than high stability.

Coherence analysis reveals key differences in the feedback control of loads according to load order, stability and visual gain. We consider first the association between disturbance and load position (Fig. 4C). For all loads, coherence generally rises with frequency: at higher frequencies load movement is highly predicted by the disturbance, unaffected by variable joystick movement. At lower frequencies, the effect of disturbance on the load movement is less predictable as a consequence of feedback, which is not linear-time invariant. If feedback were linear-time invariant, the coherence would be very high at low frequency and that is not observed here. Lower coherences are shown by 2nd order rather than 1st order, low stability and high visual gain. For the 2nd order loads, there is a notable dip in coherence between 1 and 2 Hz. This indicates greater influence on the load of variable joystick movement at these frequencies.

Coherence measures the linear association between two signals and this includes a remnant component which is randomly associated and not causally related. This component reduces by averaging more segments in the FFT analysis. Using ARMA analysis, the proportion of power in the LTI response to the disturbance represents only that power which is causally related to the disturbance. This ratio is shown in Fig. 4E: it
Figure 5. Impulse response functions (IRF's) for all loads
All curves show the closed loop IRF for time following an impulse, for each load, averaged over eleven trials (one trial for each subject). Dashed lines show 95% confidence intervals in the mean. Left and right columns represent the load and joystick, respectively. A and B show the closed loop IRF between disturbance and load and joystick, respectively. C and D show the cross correlation between disturbance and load and joystick, respectively. E shows an expanded view of panel B. The black curves in A and C show the initial open loop impulse response of the
presents a very similar pattern of results as coherence: this illustrates the meaning of the coherence measure, although the numerical values are slightly lower than the coherence since the remnant is not included. The higher numerical values for 1st order loads show that feedback control of these loads is relatively well described as a LTI process, although at low frequencies, the proportion of LTI power is still less than 50%. For 2nd order loads, the ratio of LTI power is generally lower and less than 50% across the range of manual control below 3 Hz. The lack of LTI feedback is higher when the load is more unstable or the visual gain is higher.

The coherence between disturbance and joystick (Fig. 4D) and ratio of LTI power (Fig. 4F) decreases with frequency. These low coherences and LTI power ratios do not reflect low joystick power, which is much higher than load power beyond 1 Hz; rather participants were incapable of making a linear time invariant response beyond 2–3 Hz for 2nd order and beyond 4–5 Hz for 1st order loads. The high coherence at low frequency is consistent with more effective cancellation of the disturbance at low frequency. Coherence decreases with load order (2nd vs. 1st) and instability. Control of 1st order loads is predominantly described as an LTI process below 0.4 Hz and well described at 0.1 Hz. For 2nd order loads, the lack of LTI control increase with less stable loads and more visual gain. At all frequencies, the balance of unstable 2nd order loads is not well described as a LTI process, with the ratio of LTI power decreasing from a maximum of 40% at low frequency to below 10% as frequency increases beyond the important 1–3 Hz region (Loram et al. 2005c, 2006).

The temporal response to the disturbance of the load and joystick is shown in the closed loop impulse response functions (IRFs) of Fig. 5. These show the statistical correlation between an instantaneous disturbing impulse at time zero and the load or joystick at different time shifts. The cross correlations (Fig. 5C and D) include remnant, non-causal associations prior to and after the disturbing impulse. However, the ARMA IRFs (Fig. 5A and B) show only the causal response to an impulse, show no response before time zero, and are more suitable for calculating the feedback time delay. Both methods show the same pattern of results, confirming the validity of the ARMA approach, but the ARMA approach is clearer.

Load position deviates little from the open loop response for 150–300 ms (1st order) and 400–500 ms (2nd order), respectively, and then restores to zero with or without overshoot (Fig. 5A). These durations represent an ‘effective time delay’, which includes the feedback time delay and system lag. High visual magnification decreases the response time for correcting the disturbance.

For all loads, the joystick shows a delay during which there is no joystick movement and no control is exerted on the load (Fig. 5B). This delay is the feedback time delay. Subsequently there are damped oscillations associated with a stable closed loop system. The settling time is less for 1st order and high visual gain loads. Closer examination of the delay between disturbance and joystick (Fig. 5E) shows a shorter delay for 1st order compared with 2nd order loads. First order loads show a mean delay of approximately 130 ms which is reduced by 10–20 ms with high visual gain. Responses for 2nd order loads sometimes show a non-significant positive deviation and all deviate negatively from zero at a time significantly later than 1st order responses by approximately 100 ms. The delay appears unaffected by load stability but is reduced by several tens of milliseconds by high visual gain.

Statistical analysis of the feedback time delay calculated from individual trials (Fig. 6A) shows that for 2nd order systems with normal visual gain the mean delay was 224 ± 26 ms and no significant difference was associated with stability (one way ANOVA, 2nd order (100, 85, 20%), P = 0.32). Comparing loads 2, 4, 5 and 6 (Table 1) using a two-way ANOVA (n = 44), the delay is significantly longer for 2nd rather than 1st order (P < 0.0001), is reduced with high visual gain (P = 0.0001), and the reduction is greatest for 2nd order (interaction, P = 0.004). For all 2nd order and 1st order loads the feedback time delay was 216 ± 30 ms and 124 ± 20 ms respectively. The reduction in delay associated with high visual gain was 34 ms and 8 ms for 2nd order (85%) and 1st order, respectively.

Feedback time delays estimated from the cross correlations were similar to those estimated using ARMA IRF, but were more variable and with more outliers on account of remnant included in the cross correlation (Fig. 6B).

The human feedback control effort is shown as a transfer function (gain and phase) relating movement of the joystick to load position displayed visually on the oscilloscope (Fig. 7). All participants showed adaptation of their transfer function between different loads, most dramatically between 1st and 2nd order loads. For 1st order loads, participants roughly approximated an integrator in which their gain progressively decreases with frequency (Fig. 7A). For 2nd order loads, participants showed some evidence of proportional control (constant gain at low frequency), clear differential control (increasing gain with frequency up to approximately 2.5 Hz, and bandwidth limited control (decreasing gain
with frequency beyond 2.5 Hz) or alternatively integration of the high frequency components. A ‘peak’ in gain at 1–3 Hz is discernable for all the loads, but is a marked prominent feature for all the 2nd order loads and is only a small feature for the 1st order loads. Considering the mean logarithmic gain of each load at all frequencies less than 3 Hz, there were significant differences in gain between the 2nd order systems (one way ANOVA, \( n = 307, P = 1 \times 10^{-12} \)). Post hoc pairwise comparisons using the Tukey–Kramer criterion showed that the gain was significantly increased during high vs. normal visual gain (2 vs. 3 Table 1) and during low stability (4 v each of 1, 2 and 3, Table 1). Similarly, for the 1st order load, visual manual gain was significantly increased during high oscilloscope magnification (one way ANOVA, \( n = 307, P < 10^{-12} \)).

Visual–manual phase generally showed a low frequency phase advance for 2nd order systems and low frequency phase lag for 1st order systems (Fig. 7B). When the feedback time delay is removed (Fig. 7C), the human controller shows a greater phase advance with 2nd order systems up to about 70 deg and to just beyond 73 deg for the most unstable (20%) system. Beyond 2 Hz, the phase lag increases markedly for all loads (Fig. 7B). When the feedback time delay is removed (Fig. 7C), the lag with 1st order systems approaches 180 deg at 10 Hz. After removing the time delay, considering all frequencies between 0.4 and 3 Hz, there were significant differences in phase between the six loads (one way ANOVA, \( n = 1601, P < 10^{-12} \)). Post hoc pairwise comparisons showed that the phase was significantly increased for 2nd vs. 1st order, during high vs. normal visual magnification for each order, and during low stability (20% vs. 100%) with 85% intermediate but not significantly different from either 100% or 20% loads.

**Discussion**

We have studied human visuo-manual, compensatory tracking of a variety of simulated loads. Key features of this task, are (1) proprioceptive and vestibular feedback have been excluded, (2) the control activity is sustained, rather than concerning isolated hand movements or a response to discrete stimuli, (3) the task is regulatory, resulting in small movements close to threshold uncertainty. The task is relevant to visual-manual control, control of balance and human postural control.

Four important results were clearly demonstrated.

1. The feedback delay depended primarily on load order (2nd: 220 ± 30, 1st: 124 ± 20 ms), secondarily on visual magnification (extent 2nd: 34, 1st: 8 ms) and was unaffected by load stability (Fig. 6).

2. The regulatory control was inherently variable, i.e. not LTI, and this variability increased with the order of the load and the instability of the load. For unstable (85%) loads, LTI control accounted for 40% of manual output at 0.1 Hz and this proportion decreased below 10% as frequency increased through the important 1–3 Hz region where manual power and visuo-motor gain are high (Fig. 4).

3. The human control mechanism was flexible; participants adapted their mean manual gain and phase response to the visual information according to the order and stability of the load and also according to the magnification of the display (Fig. 7).

4. The visual manual control process shows an enhanced gain at around 1–3 Hz irrespective of load order, stability or visual magnification (Fig. 7) and for 2nd order loads this was associated with a reduction in LTI feedback control (Fig. 4).

These results are significant for the following physiological questions discussed below.

1. Is the invariant frequency bandwidth when balancing inverted pendulum loads of varying stability explained by a constant feedback time delay?
(2) What physiological process – transmission, threshold detection or central processing – accounts for the feedback time delay?

(3) How does balancing an unstable load relate to human automatic or intentional responses to stimuli?

(4) Could quiet standing be better explained by a high variability, central intentional process rather than a low variability, peripherally driven process?

Technical preliminaries when interpreting the results

These results were established using non-parametric analysis and minimal assumptions. No particular view or model is required to support the findings. Cross correlation makes no assumption of causality but measures the statistical association between the continuous stimulus and closed loop feedback response and includes a non-causal component which is associated by chance. Frequency based coherence analysis measures the linearity (constant gain and phase) between the disturbance and response again including this randomly associated component. ARMA analysis is a general approach modelling the linear response that is causally related to the disturbance and excluding the remnant which is not caused by the disturbance. The high order of the ARMA models allows a ‘non-parametric’ interpretation. Good agreement between the cross correlation and ARMA estimates of the delay (Figs. 5A–D and 6) and linearity (Fig. 4C–F) corroborate the findings. The statistical significance of differences in the delay between load conditions is very high: there is little ambiguity in effects of load order and visual magnification.

An impulse response function (IRF) shows a duration for which the magnitude is indistinguishable from zero, and then a curve deviating from zero. The duration for which the IRF is zero represents the time delay. The curve is associated with phase lags in the closed loop response.

The delay calculated from the closed loop IRF is the average duration for which there is no linear-time-invariant feedback response to the disturbance. This could result from a linear-time-invariant process of fixed delay or could represent the combined result of variable processes of variable delay. However, the delay is a genuine delay preceding any corrective movement. Hence the delay is attributed to threshold detection, transmission time and processing and not the low pass dynamics of the load, muscle and limb. This feedback delay must be carefully distinguished from the longer ‘effective delay’ which additionally includes those phase lags due to the load and musculo-skeletal response. The ‘effective delay’ includes both the feedback delay (i.e. the time before the start of the control response) and the time for control response to significantly change the load behaviour from the open loop response. We measured this larger ‘effective delay’ to be 0.4–0.5 s and 0.15–0.3 s, (2nd and 1st order respectively) (Figs 2B and 5B, D and E). Using visuo-manual control tasks, previously published values of the delay for 2nd and 1st order loads are 400–500 ms and 150–300 ms, respectively (McRuer & Jex, 1967) and (p. 398 of Wickens & Hollands, 2002). These previous values agree well with our estimate of the longer ‘effective delay’ after which load movement deviates significantly from open loop behaviour (Fig. 5A and C). Thus we understand previous values as reporting the longer ‘effective delay’ rather than the shorter feedback time delays of 220 and 124 ms (2nd and 1st order, respectively) which we have presented here.

A 1st order load introduces a phase lag of up to 90 deg, while a 2nd order load produces a lag of up to 180 degrees. With the same time delay for both 1st and 2nd order loads, could the 100 ms observed difference in estimated feedback time delay be due to incomplete compensation for second-order load dynamics in the subject’s internal model? Incomplete compensation seems to be the norm in human tracking, and one notes (Fig. 7) that the difference in phase up to about 1 Hz between 1st and 2nd order loads is about 70 deg, not 90. In response to this question, Fig. 5E shows that the difference in time delay between the 1st and 2nd order loads of approximately 100 ms is not associated with phase lags but is genuinely associated with differences in time delay; the duration after which the IRF departs from zero differs by about 90–100 ms between 1st and 2nd order loads.

Non-linearities in the closed loop response can result from several sources (p. 134–139 of Poulton, 1974) including (1) phase variability or equivalently temporal variation in the feedback delay, (2) discrete and/or intermittent control with open loop periods of insensitivity to feedback information (Ronco et al. 1999; Gawthrop, 2004; Gawthrop & Wang, 2006, 2007), (3) abrupt, impulsive control including ‘on–off’ control or crossing a threshold, (4) motor noise such as tremor, and (5) instrumental measurement noise, which was negligible in these experiments. Regulation of the 2nd order loads was predominantly non-linear and the non-linearity increased with load instability (Fig. 4C–F).

Is the invariant frequency bandwidth when balancing inverted pendulum loads of varying stability explained by a constant feedback time delay?

Strikingly, the feedback time delay was not altered by the stability of the 2nd order loads (Fig. 6). Decreasing load stability makes balance (control of equilibrium) more difficult because it decreases the load time constant and increases the required upper frequency limit on the control bandwidth. If participants were able to reduce their time delay, this would increase the control bandwidth.
Figure 7. Open loop visual-manual transfer function for all loads

The visual manual transfer function represents the open loop gain and phase between load position and joystick position. It characterises the human feedback controller (Fig. 1). All curves show variation of the quantities with frequency, for each load, averaged over eleven trials (one for each subject). Dashed lines show 95% confidence intervals in the mean. A, gain; B, phase; C, phase after removing the phase lag due to the estimated time delay.
Note also, that although the visuo-motor gain increased to attempt to compensate for more unstable loads, the frequency of peak gain did not increase (Fig. 7A). The fact that participants were unable to reduce their delay demonstrates the existence of a physiological constraint. This result is consistent with previous findings that the frequency of manual balance adjustments is constrained by intrinsic physiological factors and confirms that the feedback time delay underlies that constraint (Loram et al. 2006). Moreover, it has been previously observed that during quiet standing the frequency bandwidth of sway and control output is remarkably constant during a wide range of sensory conditions: the reason for this invariance has been unknown (Jeka, 2006; Lakie & Loram, 2006). An irreducible feedback time delay provides an explanation of this phenomenon.

What physiological process – transmission, threshold detection or central processing – accounts for the feedback time delay?

The feedback time delay was primarily determined by the order of the load (Fig. 6).

For 1st order loads, the delay of 124 ± 20 ms is longer than the sum of sensory and motor transmission delays 60–75 ms (40–55 ms for the visual information to reach the brain (Pratt et al. 1995), and 20 ms for the efferent signals to reach the hand (Rothwell et al. 1991)). Thus nearly half the delay (and probably most of the variability) is explained by central neural processing. Since very large changes in visual magnification reduced the mean delay by 8 ms, only a small part of the delay and a minor part of the processing are associated with waiting for unpredicted load movements to cross perceptual thresholds.

With 2nd order loads, the feedback delay is approximately 100 ms longer at 220 ± 30 ms (Fig. 6). Given the same transmission delays, the duration of processing has increased from approximately 54 (124 ms – 70 ms) to 150 ms. In addition to the longer delay, the variation in delay between subjects was also greater (Fig. 6). Very large increases in visual magnification produced larger (34 ms) reductions in delay, which might be associated with movement detection. The 34 ms delay associated with thresholds is a secondary factor relative to the difference in delay between 1st and 2nd order loads, which is primarily attributed to a difference in processing (Fig. 6). Thus the delay in controlling 2nd order loads is primarily associated with central processing.

How does balancing an unstable load relate to human automatic or intentional responses to stimuli?

The difference between automatic and intentional control. The extent to which responses are modifiable by voluntary intention increases as the latency increases. The direction of the short, medium and long latency reflexes (M1, M2, M3) evoked by sudden flexor displacement of the wrist, cannot be altered by the subject’s prior intention but to some extent the amplitude can. The variation in latency is small (Rothwell et al. 1980; Loo & McCloskey, 1985). Voluntary or intended responses to a jolt of the wrist that does not involve muscle stretch can be modified in direction as well as in amplitude, have a longer latency and contain substantial variability in latency (Tatton & Lee, 1975; pp. 115–118 of Brooks, 1986). This difference in temporal variability between reflex and intended responses indicates that they are stimulated and produced by different processes – peripheral muscle stretch and central initiation, respectively. In a highly relevant experiment, it has been shown that the shortest latency of finger movement responses to unpredictable changes in visual target position occurred at 120–160 ms (Day & Lyon, 2000). These authors reported that automatic finger movements at this latency could be modified in amplitude but only follow the direction of the jump in target and could not oppose it. Intentional control over the direction as well as the amplitude of the response was possible at latencies of more than 160 ms.

How does the control of 1st and 2nd order loads relate to automatic and intentional control?. The 1st order time delay is shorter than a simple visual reaction time of 180–200 ms (Brebner & Welford, 1980) and similar to ‘automatic’ finger movement responses to a jump in visual target (Day & Lyon, 2000).

The longer delay of 2nd order loads places the feedback control clearly in the ‘intended control’ category. In the previously referred to work (Day & Lyon, 2000) latencies of more than 160 ms were associated with control over the direction as well as the amplitude of the response. The joystick movement beyond 0.5 Hz is very poorly described as LTI (Fig. 4D and F): this is strongly consistent with intentional control.

Why is the delay longer for 2nd than for 1st order loads?. If control proceeded by setting the set-point, gains and thresholds of a peripheral regulatory servo, then one would...
expect the feedback time delay to remain the same and the variability to remain low (Crago et al. 1976). On this view, position error and velocity and even acceleration would be sampled with minimal delay (Lockhart & Ting, 2007; Tresch, 2007; Welch & Ting, 2008), and providing the feedback gains were appropriate having been learned and refined by experience, regulation would be automatically ensured.

However, if regulation requires online processing and intentional control, there would be a difference. Second order loads have mass whereas 1st order loads do not. Thus, positional errors of a first order load are corrected by a monophasic movement, or throw of the joystick; furthermore the throw is always in the same direction with respect to the error, i.e. towards the centre (p. 324 of Poulton, 1974). Control of this sort could be achieved using only amplitude modulation with a delay of 120 ms (Day & Lyon, 2000). Positional errors of a 2nd order load are corrected by a biphasic movement or throw and catch of the joystick (Poulton, 1974; Loram & Lakie, 2002b): the mass has to be accelerated in the intended direction (throw) and then decelerated to rest at the corrected position (catch). Moreover, the direction of the initial throw is not certain. If the positional error is positive and the velocity is positive, the initial throw should be negative i.e. towards the centre. If the positional error is positive and the velocity is negative (towards the centre), the initial throw may need to be positive. For a given positional error, the control mechanism must be capable of varying direction of response as well as amplitude depending on the velocity of the load. Control with this facility takes longer than the duration required for amplitude only modulation (p. 116 of Brooks, 1986) and according to one study takes at least 160 ms (Day & Lyon, 2000). In comparison with 1st order loads, 2nd order loads would require more information to be taken into account (velocity as well as position); more complex responses need to be prepared and this takes longer.

LTI mechanisms stabilise the load by constructing what are functionally neuro-mechanical springs and dampers embedded neurally in the spinal cord, brainstem, cerebellum, etc. The job of the nervous system then becomes that of calculating a desired position and all else follows automatically. The complexity of the load doesn’t matter. During visually guided manual control of unstable 2nd order loads there were substantial feedback delays and the control process was not LTI (Fig. 4). These features did not result from our exclusive use of visual inputs because we found much shorter delays and a greater degree of LTI control when subjects visually controlled a 1st order load. Rather, these results suggest that delay and variability are an inevitable consequence of the need to construct complex output trajectories to control 2nd order loads.

Unanswered questions. For second order loads the visuo-manual response showed an enhanced gain (Fig. 7A) and variability (Fig. 4C and E) in the 1–3 Hz region: these features represent the main difference between control of 2nd and 1st order loads. The increasing gain with frequency at 1–2 Hz (Fig. 7A) is associated with differential action, i.e. the use of velocity information. The time delay (Fig. 6A), the increased variability (Fig. 4C and E) and comparison with known physiology indicate a central, intentional control process in which the delay between stimulus and response is variable. We ask whether this enhanced sensitivity and variability at 1–3 Hz is intrinsic to human motor control independently of what is being controlled. We note that in remnant form this sensitivity at 1–3 Hz appears when controlling 1st order loads as well as all stable and unstable 2nd order loads (Fig. 7A); also 1–3 Hz is the frequency of intermittent, hand action in pursuit and compensatory tracking of moving targets (Miall et al. 1993); and 1–3 Hz is the frequency of intermittent muscle action during quiet standing (Loram et al. 2005c).

Could quiet standing be better explained by a high variability, central intentional process rather than a low variability, peripherally driven automatic process?

How does visually guided manual control relate to standing balance?. Unlike visually guided manual tracking, standing balance has access to proprioceptive and vestibular mechanisms. Two distinguishable mechanisms may contribute to the control process: automatic mechanisms stimulated by peripheral muscle stretch (and vestibular acceleration) and intentional mechanisms stimulated by central initiation. Which mechanism predominates will likely depend on whether or not there is a clear muscle stretch or vestibular stimulus representing bodily sway.

Balance on a translating platform has been advocated as representing quiet standing. Most published values of the time delay during the regulation of posture and balance result from experiments in which standing humans are disturbed by platform translations and rotations. It has long been known that functional stretch reflexes with a latency of approximately 100 ms help to stabilise the participant during platform translations and that the gain of these reflexes can be modulated according to whether they are appropriate for the perturbation (Nashner, 1976). It has been largely assumed that this paradigm is also representative of normal (unperturbed) regulation of posture and balance and that it demonstrates that standing posture and balance are regulated by functional stretch reflexes (p. 121 of Brooks, 1986) or a generalised feedback
During quiet standing, the bodily sways are a few tenths of a degree at approximately a tenth of a degree per second (Loram et al. 2005c). The associated ankle rotations are too small and slow to effectively stimulate peripheral servo mechanisms (p. 537 of Pierrot-Deseilligny & Burke, 2005; Loram et al. 2007a). Moreover, high short range contractile stiffness, the high tendon compliance and the paradoxical muscle movements associated with regulating muscle activity to maintain quiet standing ensure that the agonist spindles are unlikely to register postural sways (Loram et al. 2005b, 2007a,b, 2009). In addition, during quiet standing sways the vestibular stimulus is an order of magnitude below the perceptual threshold (Fitzpatrick & McCloskey, 1994). During quiet standing, we propose there is no clear, unambiguous muscle stretch or vestibular stimulus representing bodily sway which would peripherally drive the control process. The velocity information is highly ambiguous and the direction of the required response uncertain meaning that the control-demand is complex rather than simple. Unlike platform translated standing, where LTI equations can compute control output (calf muscle activity and ankle torque) from the disturbance and joint rotation (van der Kooij & de Vlugt, 2007; Welch & Ting, 2008) this is not possible for quiet standing, which is characterised by high variability and can only be modelled stochastically (Kiemel et al. 2006). Lengthening and shortening of the calf muscles is a better indicator of control output than ankle torque, since ankle torque contains a substantial passive contribution from the intrinsic ankle stiffness (Loram & Lakie, 2002a; Loram et al. 2007a), which is high during quiet standing and which has a relatively time-invariant relationship with bodily sway. Ultrasound tracking of calf muscle movements shows irregular fluctuations similar in nature to the manual movements during compensatory tracking (Loram et al. 2005c) (Supplemental material). The feedback delay during quiet standing is unknown and not easily measured since adding a disturbance changes the nature of the task. However, time-locked averaging of micro-falls during quiet standing shows the acceleration of the fall precedes the subsequent, associated, corrective rise in muscle activity by 370 ms (Loram et al. 2005c). This association analysis is consistent with a longer feedback delay during quiet standing than during platform translation experiments. Since peripherally driven automatic mechanisms are unlikely to be effective, centrally initiated, intentional mechanisms may be required: this idea is supported by dual task experiments into quiet standing, which are consistent with the idea of a cognitive component in the control process (Pellecchia, 2003).

Key differences between platform translated and quiet standing. These platform translations produce large amplitude, high velocity muscle stretches, considerably above the threshold required to elicit strong peripheral and automatic responses. These muscle stretches provide unambiguous velocity and position information relating to joint rotation and bodily sway. Equally, the head movements are considerably above the vestibular threshold (Fitzpatrick & McCloskey, 1994) and also provide unambiguous information related to bodily sway. Consideration and examination of discrete translations (Fig. 3 of Welch & Ting, 2008) shows that the corrective response is always directed in the opposite direction to the disturbance. There is no ambiguity in the direction of the required response and thus the control demand is simple rather than complex. The nature of the response is highly time invariant (van der Kooij & de Vlugt, 2007) consistent with an automatic process. This peripherally driven mechanism achieves initial stabilisation in the face of a strong disturbance but it is not demonstrated that it achieves fine regulation of position and equilibrium (cf. Fig. 3 of Welch & Ting, 2008). In fact, continuous pseudo-random, large, high acceleration platform translations produce an increase in the absolute amount of remnant, i.e. non LTI sway (van der Kooij & de Vlugt, 2007), which demonstrates that the peripherally driven mechanism does not achieve fine regulation of position and balance. Moreover, the proportion of LTI responses increases when the amplitude of translations increases from 6 to 8 cm (van der Kooij & de Vlugt, 2007): thus platform translations stimulate a process which is not so prevalent when the translations are smaller or absent all together. Amplitude modulation of the functional stretch reflexes, which have little temporal variation and rapid response (p. 118 of Brooks, 1986), is an adequate mechanism for partially countering these disturbances. Is this process a good model for quiet standing where of course there are no external perturbations?

Visually guided control of 2nd order loads can explain the variability in quiet standing. We propose that in the absence of an effective, externally driven muscle

© 2009 The Authors. Journal compilation © 2009 The Physiological Society
stretch-vestibular mechanism, regulation of the human inverted pendulum during quiet standing is essentially the same process as manual or pedal compensatory tracking of an unstable second order load. This hypothesis is not proven, but is well supported by argument and evidence (Supplemental material), (Fitzpatrick et al. 1996; Lakie & Lakie, 2002b; Lakie et al. 2003; Loram et al. 2005b,c, 2006, 2009; Lakie & Loram, 2006; Chew et al. 2008). These considerations argue that normal regulation of posture and balance may be more closely represented by the control of unstable 2nd order loads presented here than by large platform perturbations of standing humans. If correct this task predicts a feedback time delay of approximately 220 ms, and an ‘effective delay’ of 400–500 ms during quiet standing. This paradigm provides a physiological explanation of the variability observed during quiet standing. Rather than explaining the variability as a LTI (e.g. PID or optimal) controller driven by large quantities of sensory noise (Maurer & Peterka, 2005; van der Kooij & de Vlugt, 2007) or computational noise (Kiemel et al. 2006), variability is explained physiologically as resulting from intentional control. Intentional control has more temporal variation in the central initiation of control outputs than automatic peripherally driven responses. Intentional control is thus a non-linear process.

The existence of a peripherally driven mechanism, effective and dominant during large platform translations, does not exclude simultaneous operation of intentional mechanisms with a longer latency controlling the finer regulation of position and equilibrium. We suggest a mixed model of a peripherally driven LTI servo for partially rejecting large disturbances and intentional control for fine regulation of human balance.

When perturbations are sinusoidal, including a sum of sinusoids where the amplitude decreases with frequency (Kiemel et al. 2006), there is the likelihood of prediction particularly of the large low frequency components, which reduces the measured time delay (Neilson et al. 1988b).

Conclusions

Having examined visuo-manual control of a variety of loads, we observe clear differences between the control of 2nd and 1st order loads. The delay and variability identify 2nd order control as intentional and 1st order control as automatic, i.e. requiring voluntary control over amplitude but not direction of response. Unlike platform translation experiments, during quiet standing muscle-stretch and vestibular input do not provide clear stimuli to evoke a useful response: thus balance of an external, unstable load arguably provides a closer representation of the quiet standing process. If standing is the same process as visuo-manual control of an unstable 2nd order load then there are substantial feedback delays and the control process will not be LTI. These features do not result from our exclusive use of visual inputs because we found much shorter delays and a greater degree of LTI control when subjects visually controlled a 1st order load. Rather, our results suggest that delay and variability are an inevitable consequence of the need to construct complex output trajectories to control 2nd order unstable loads. This may imply that the variability observed in quiet standing, and more generally in movement control, may indicate flexible, variable delay, intentional mechanisms rather than the automatic LTI mechanisms usually reported in response to large perturbations.

Other methodological problems with estimates of the time delay in human standing. Existing values of the time delay have been derived during disturbed standing experiments. There are further reasons for doubting these values as estimates of the time delay during quiet standing.

In some cases the time delay has been estimated by tuning a simple delayed feedback model to fit the stimulus–response data (Peterka, 2002; Welch & Ting, 2008). Whether or not the estimated delay is correct depends on whether the model is physiologically accurate. For example, including or not including a predictor in the feedback controller alters the estimated time delay (manuscript in preparation).

With continuous perturbations, the frequency range of the stimulus and the analysis of the stimulus–response data are often limited to low frequencies below 4 Hz (Peterka, 2002; Kiemel et al. 2006; van der Kooij & de Vlugt, 2007), whereas accurate estimates of the time delay require stimulus–response analysis at higher frequencies.

The loads used in these experiments are based on the dynamic bias model of human standing (Lakie et al. 2003; Loram et al. 2005b). This model, consistent with ultrasound observations of the calf muscles during standing, assumes that ankle torque is applied to an inverted pendulum human via a muscle tendon unit comprising a compliant tendon in series with a contractile unit which generates force. Mathematically, this is equivalent to an ankle torque comprising an active (neurally modulated) and a passive component.

The equation of motion for the inverted pendulum is:

$$J \ddot{\theta} = mg h \theta + T$$

where $J$, $\theta$, $m$, $g$, $h$ and $T$ are respectively the moment of inertia, angle from the vertical, mass, gravitational acceleration, height of centre of mass and ankle torque.
The ankle torque, $T$, is given by

$$T = -cmgh(\theta - \theta_0) - B\dot{\theta}$$

which separates into active, $cmgh\theta_0$, and passive, $-cmgh\theta - B\dot{\theta}$, components where $c$ is the tendon stiffness relative to the load stiffness $mgh$, $\theta_0$ is the neurally modulated bias or contractile element length, and $B$ is the passive ankle viscosity. Combining both equations and expressing in Laplace transform notation gives:

$$\theta = \frac{cmgh}{s^2 + \frac{B}{T} s + (c - 1) \frac{mg}{T} \theta_0} = \frac{a}{s^2 + \frac{B}{T} s + (c - 1) \frac{mg}{T} \theta_0}$$

The loads used in these experiments were derivatives of this transfer function. The numerator coefficient, $a$, represents the coupling between the bias $\theta_0$, which in practice is given by joystick movement, and load position $\theta$. We decided to keep this coupling constant for all the loads using a value of $c = 0.85$, which represents a normative value for unperturbed regulation of upright balance (Loram & Lakie, 2002a; Casadio et al. 2005; Loram et al. 2005b, 2007a; Gawthrop et al. 2008). Thus $a = \frac{0.85mgh}{T}$. The denominator coefficients determine the passive stability and time constants of the load. These were varied to give the following second order loads:

1. standard unstable, dynamic bias model: $c = 0.85$,
2. stable, dynamic bias model: $c = 1$,
3. reduced stability, dynamic bias model, $c = 0.2$.

Stable 1st order loads were obtained by removing an integrator and the gravitational-tendon components giving a transfer function of:

$$\theta = \frac{a}{s + \frac{B}{T} \theta_0}$$

References


Acknowledgements
We acknowledge EPSRC financial support for this project via the linked grants EP/F068514/1 EP/F069022/1 and EP/F06974X/1. We thank Dr H. Gollee for his helpful, critical comments in revising the manuscript. We wish to thank the anonymous volunteers for their enthusiasm and time in carrying out these experiments.

Supplemental material
Online supplemental material for this paper can be accessed at: http://jp.physoc.org/cgi/content/full/jphysiol.2008.166173/DC1