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Balancing During Virtual Motions

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We can wonder at the balance skills of the gymnast, ballerina and tightrope walker. Yet our own balance skills are almost as impressive, enabling us to go about our many everyday activities without crashing to the ground. The balance system deals with the constant pull of gravity on all parts of the body, a mechanical structure that is intrinsically unstable when upright. It is a complex process involving many senses. We would dearly like to know how the brain performs this delicate balancing act. What are its principles of operation? Which central nervous structures are involved? What are their functions? We are a long way from answering these fundamental questions but a number of labs around the world have started to make some headway using a variety of approaches. My intention here is to introduce briefly some of our own experiences in this area.

One of our research interests has been to understand how information from the vestibular system (semicircular canal and otolith organs in the inner ear) contributes to balance control. The vestibular system signals angular and linear accelerations of the head in three dimensions. It therefore furnishes the brain with information about how the head is moving and orientated in space. Because movements of the body cause the head to move in space, vestibular information has an important role to play in the control of balance.

From the outset it was clear that before we could begin to tackle this question two problems had to be overcome. The first is a general measurement problem common to all experiments on people engaged in balance tasks. How can we measure the person's behaviour without interfering with the very process that we wish to study? Any measuring device that gives the slightest sensory cue about body motion, or that acts as a constraint in some way, may alter balance behaviour. The developments of forceplates and optoelectronic motion analysis systems have solved this problem. Because the sensors do not constrain movement and do not provide any feedback to the subject, they offer an ideal tool for capturing balance behaviour.

The second problem is more specific. How can we investigate the vestibular system's contribution to balance, both non-invasively and while subjects are performing a balancing act? One option, of course, is to perturb the head in some way and see how the body responds. This is a messy approach because a controlled perturbation of the head in space requires that an external force be applied. That force, apart from perturbing the vestibular system, would inevitably disturb other sensory systems at the same time. Our solution to this problem has been to use an electrical stimulation technique in which a small DC electric current (~1mA) is passed between surface electrodes placed behind the ears **(fig 1)**. This technique, which was discovered over 100 years ago, is known as galvanic vestibular stimulation or GVS. We now know that it works by altering the signal that is continuously fed into the brain by the vestibular nerves. The net effect of all these changes in firing of vestibular nerves is a sudden and maintained change in vestibular input that is similar to a signal produced by a natural movement of the head. In other words, GVS may be thought of as a virtual head movement. Reversing the stimulus polarity produces a virtual head movement in the opposite direction.

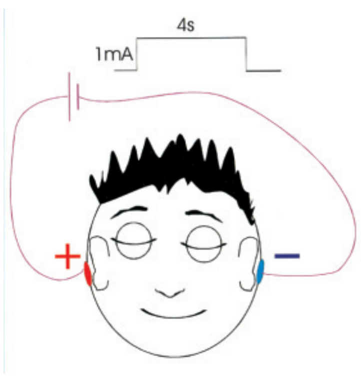

Fig 1: The technique of galvanic vestibular stimulation (GVS) provides a means of perturbing the vestibular system in isolation. A rectangular waveform of current is passed between electrodes fixed over the mastoid processes.

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Motion Capture and the Progress of Science

Dudley S. Childress, Ph.D.

In 1991, I was in Copenhagen for a meeting of the International Society for Prosthetics and Orthotics (ISPO) and took opportunity to visit the island of Hven between Denmark and Sweden. Hven is the location where Tycho Brahe made historic astronomical observations of the planets. Tycho himself wore a prosthesis, an artificial nose made of silver and gold. Nevertheless, it was his sky observations, beginning around 1577, that made him famous. His observatory was first at Uraniborg but this house-like structure was inadequate for observing, partially because of mechanical vibrations. He had a better observing facility built nearby, called Stjerneborg. The improved equipment was positioned partly below ground, which greatly reduced vibrations. The photograph with this article, taken by the author, shows the Stjerneborg observatory. Accuracy of the equipment was around 0.5 minutes of arc, which was several times more accurate than other existing systems at that time. Tycho later moved to Prague and it was there that Kepler joined him as an assistant around 1600. After Tycho's death in 1601, Kepler was able to use the collected data in determination of his three laws of planetary motion. This was a big step forward in celestial mechanics and would have a strong impact on Newton. Tycho's instruments and measurements helped change the direction and progress of science.

Replica of Tycho Brahe's Stjerneborg observatory on the island of Hven. The facility was placed below ground to minimize mechanical vibrations of the equipment. Motion analysis equipment has often been placed in the basement of buildings for the same reason. Observations were made through an aiming apparatus that relied on the naked eye for sighting and for reading the angular measurements. The methods were crude but the accuracy turned out to be sufficient for Kepler's needs.

Can this rather strange technique be used to probe the human balance system? It seems so. GVS applied to a person engaged in a balance task produces a whole-body balance response. The response is automatic and directed to muscles throughout the body. In a person standing with eyes closed and head facing forwards, the stimulus causes a sideways motion culminating in a lateral lean and bend of the body. As shown in **fig 2,** all body segments become tilted laterally with each segment being tilted more than the segment below it. A reversal of stimulus polarity produces an identical response in the opposite direction. We think of this response as the compensatory action of the balance system to a head movement, albeit virtual, that is interpreted by the brain as resulting from an unwanted body movement.

The major advantage of GVS is that it allows us to perturb the vestibular system in isolation without directly affecting any other sensory system. This is not to say that other sensory systems do not influence the response. On the contrary, we find that the response to GVS is critically dependent upon sensory information available from non-vestibular sources. An example is given in **figure 3**, which shows the response from a person who has lost all large-fibre sensory input from his body below the collar line. In this experiment we looked at his responses during sitting since standing with eyes closed was too difficult for him to manage. The striking result was that his responses were extremely large, in fact an order of magnitude larger than those seen in healthy people under the same conditions. We suspect this is due to a gain-control process that continuously adjusts the weights of each sensory channel's contribution to balance. For our deafferented subject sitting with eyes closed, the gain of the vestibular contribution to balance was turned right up since there was no other sensory information available to his balance control system.

A different process provides another example of interaction between vestibular and non-vestibular information. The problem for this process is the following. The vestibular organs are locked inside the skull and can therefore only signal head movement in skull coordinates. The head, however, can adopt a whole range of positions relative to the body. Consider a vestibular signal that tells you your head is moving sideways as a result of a body sway. If you were facing straight ahead this would mean that your body is falling sideways. If, however, you were looking over one shoulder it would mean that you are falling backwards or forwards. Clearly, different muscle activation patterns are required to arrest these different falls.

To control balance, therefore, the brain has to combine vestibular information with all those other signals that tell it how the various body segments are orientated with respect to each other. This transformation process is clearly revealed by GVS. As shown in fig 4, the

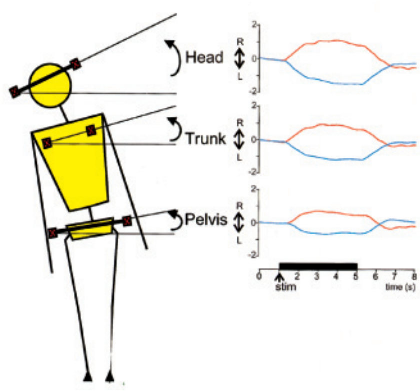

Fig 2: GVS evokes a whole-body tilt response. With the anode on the right (red traces) the body tilts to the right. With the anode on the left (blue traces) the body tilts to the left. The head tilts more than the trunk, which tilts more than the pelvis. (Adapted from Day, Severac Cauquil, Bartolomei, Pastor & Lyon (1997) Journal of Physiology, 500.3, 661-672)

direction of body sway produced by GVS is locked to the orientation of the head. Incidentally, this figure illustrates the response of people with Parkinson's disease. Because their direction of body sway is perfectly normal we can rule out a disruption of this process as being responsible for their postural instability.

My third example of sensory interaction is concerned with a mechanism that distributes motor output to the two legs. If we stand on two forceplates, one for each foot, it is possible to measure the contribution of each leg to the overall response. The change in reaction force between each foot and the ground tells us how each leg is acting to accelerate the body. We find that both legs are used to initiate the balance response to GVS. However, the contribution made by each leg depends upon the load being taken through it. This can be observed in a person standing asymmetrically with more body weight being taken through one leg than the other. Both legs continue to respond but now the response in the more loaded leg is increased whereas in the unloaded leg it is decreased **(fig 5)**.

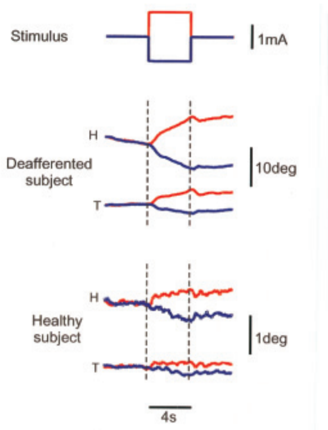

Fig 3: GVS-evoked tilt response of the head (H) and trunk (T) in a deafferented subject. The traces were obtained while seated and eyes closed, which in healthy subjects leads to very small responses (bottom traces). He tilts relatively normally towards the anodal ear (red traces anode right; blue traces anode left) but the calibration bars show that his responses are approximately ten-fold greater than normal. (Adapted from Day & Cole (2002) Brain 125, 2081-2088)

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In a small article, "Miracles of Rare Device," which appeared in The Sciences (March/April 1999), Freeman J. Dyson notes the value of tools in advancing knowledge. He supports the ideas of historian of science Peter L. Galison, who in his book Image and Logic (1997) has emphasized the importance of mechanisms in scientific endeavors. Dyson notes in his article that "…Galison emphasized tools, not concepts, as the key force driving scientific progress."

Devices have been especially important in the quantitative description and understanding of human and animal motion. Apparatus for motion capture has a long history. The field of artificial limbs (prosthetics) has played a role in this history, particularly the work of Verne Inman, M.D., Ph.D., at the University of California (Berkeley and San Francisco). Inman received funding from the United States government at the end of WWII to develop technical methods for quantitative studies of human walking on artificial limbs. The equipment turned out landmark results for the field of prosthetics. Another landmark event in the development of tools for motion capture was the funding of an international symposium (February 2-3, 1990) in Berlin by the Otto Bock Foundation (Otto Bock is an international German firm devoted to the field of prosthetics and orthotics) and the Technical University Berlin. The Proceedings (in English and German) is entitled Gait Analysis: State-of-the-art of Measuring Systems and their Importance in Prosthetic and Orthotic Technology (eds. U. Boenick and M. Näder) and was published in 1991 by Otto Bock Stiftung and printed in Germany by Mecke Druck und Verlag, 3408 Duderstadt, Postfach 1420 ISBN 3-923453-31-0.

The symposium occurred at a prescient time. Motion capture systems of many kinds had been developed worldwide and were being used with varying degrees of success. Personal computers were becoming fast and widely available at low costs. The Cold War was ending and this change was felt nowhere more strongly than in Berlin. David Mitchelson, who reported on development of the CODA System at the symposium, left Berlin a few days later with the flu. During his recovery in the U.K. he conceived the Codamotion system.

Today's tools for motion analysis are at a high level of development. The data is available for new understanding of human locomotion and for development of new ideas on how to design improved artificial legs. The situation takes us back to Tycho's data and to Johannes Kepler's insights on the data. Codamotion and other systems are providing the data needed. Now all we need are a few modern Keplers to interpret it scientifically. We need both Galisonian gadgets and Keplerian concepts.

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Similar load-dependent effects can be seen when extra weights are attached to the body. Although the receptors that signal these load changes have yet to be established, the main point is that this is another instance of a mechanism that combines sensory information from vestibular and non-vestibular sources to control stance.

With these few examples I have tried to give a flavour of our approach to the study of human balance. To finish I would like to draw attention to a methodological aspect of our work that may be applicable to other fields of motion analysis. In our experiments we invariably use a procedure that we term conditional averaging (shown schematically in **fig 6)**. There are two main components to this procedure. First, we repeat each experimental condition a number of times so we can compute the average response. This is because the single-trial response is often small, variable and superimposed on top of continuous, random body movements that are always present, even in people trying to stand still. The averaging procedure tends to cancel out the uncorrelated 'noise' and reveal the mean response. The second component involves randomly intermixing the various experimental conditions within a sequence of trials. This ensures that subjects remain uncertain of precisely what will happen in any one trial. It also irons out the unwanted effects due to time-varying changes of uncontrolled variables that could influence balance behaviour. These could arise from changes in tiredness, mood, motivation and so on.

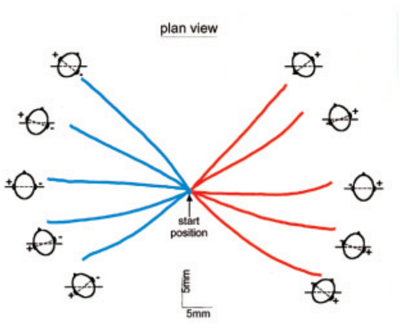

Fig 4: Plan view of superimposed excursions of the body at the level of the neck (C7) during GVS while facing in different directions. In this figure the feet are always in the same position (pointing up the page) and the head icons indicate head orientation. The stimulating anode was either on the right (red traces) or the left (blue traces). Shown are the mean responses obtained from a group of subjects with Parkinson's disease. Note that the body always sways towards the anodal ear. (Adapted from Pastor, Day & Marsden (1993) Brain, 116, 1177-1190)

For these reasons conditional averaging has become a standard method used in neurophysiological research, and possibly other disciplines. However, I am not aware of any motion analysis system that supports this method. At present, all the necessary manipulations of sorting and averaging have to be done off-line on exported data. While this approach works it does not allow us to visualise the running average of each condition while the experiment is underway, which often could be useful. Perhaps this situation would change if manufacturers could be convinced of the general usefulness of such a feature. But that would require lobbying from the motion analysis community.

Acknowledgement: *I am indebted to Richard Bedlington, who died earlier this year, for his creative technical input to all our projects.*

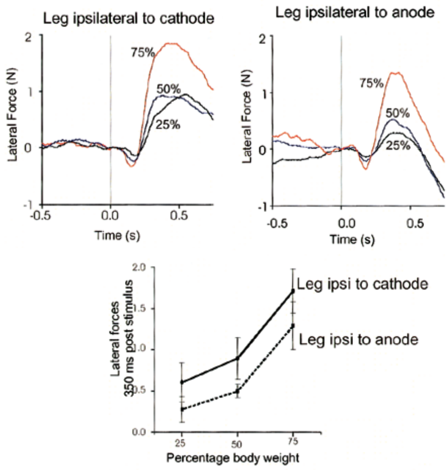

Fig 5: The mean initial response to GVS obtained from the lateral component of ground reaction force recorded under each foot separately. Subjects stood with 25% (black), 50% (blue) or 75% (red) of their body weight being taken through a leg by leaning slightly to one side or the other,. The bottom graph shows that the leg on the side of the cathode tends to produce a greater force response. However, for both legs the initial response size increases with load. (Adapted from Marsden, Castellote & Day (2002) Journal of Physiology 542.1, 323-331).

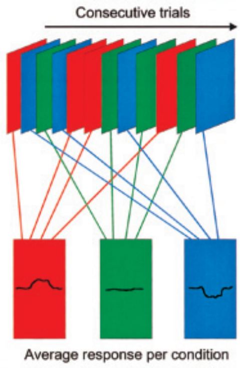

Fig 6: Schematic of the conditional averaging method. In this example, four trials of each of three experimental conditions (red, green, blue) are randomly intermixed in consecutive trials during an experimental run. These are subsequently sorted and averaged for each condition

Experiencing the scope of CODA

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The assessment of human motion, in particular gait, is becoming increasingly popular in medical research and within the clinical setting. The importance and benefits of gait analysis specifically have been widely recognised in many different clinical fields and there are now gait analysis services, or access to them, in many cities within the UK. Several years ago the parents of a Nottingham child with cerebral palsy were having to travel down to London for their daughter to be assessed. Their orthopaedic surgeon in London commented on the lack of gait labs around the UK. The pro-active parents approached Consultants in Nottingham with the idea of setting up a lab in Nottingham with charity funding. The First Step Appeal was established and fundraising began.

The First Step Appeal donated money to set-up the initial lab at Queen's Medical Centre housing a single unit CODA motion analysis system and force plates, with a research physiotherapist funded to set-up and run the service. Several years and physiotherapists later, the lab is now housed in the Clinical Sciences Building on the City Hospital site, and is owned by the Division of Physiotherapy Education, University of Nottingham. When this building was built prior to transfer, the lab was made specifically for housing the motion analysis equipment and has a 16m central walkway with 3 CCTV cameras sited at either end and to one side of the walkway to facilitate the assessment of human performance. My post as a research physiotherapist was set-up in 2001 as a joint venture between the University and Broxtowe-Hucknall PCT who provide funding for the clinical 'half' of the post.

The CODA system was one of the first pieces of kit to be demonstrated by one of my colleagues on arrival. Although the idea of motion analysis was exciting, the prospect of learning how this highly technological and complex system worked was terrifying, even though I considered myself to be a fairly technologically-minded physio. However, after a few practises with close guidance, and plenty of patience from my colleague with my unending questions, I was soon (within a month) leading the set-up process in a patient assessment session without too many hiccups.

The CODA system is very straightforward and logical, and it did not take very long before I was able to 'play' with the graph set-up and other functions, even if merely to change the colour or graph content!

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The main advantage I can see that CODAmotion has over passive marker systems, from visits to other labs and discussions with fellow gait analysts, is the ease and speed with which the reports and graphs are generated thanks to its automatic tracking and identification of markers. The immediate viewing of the stick figure is a definite plus, helping with explanations within the session to patients and parents, and providing encouragement to non-compliant children to continue, even if just to see their stick figure appear on screen.

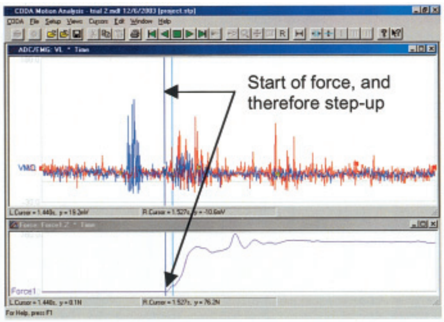

Fig 1. Showing results from assessment of VMO and VL activity during step-up, using force plate to determine onset of step.

Cycle marking is then also relatively quick, and improves with experience, and allows the results to be fairly promptly displayed in the report generator to show visiting clinicians (e.g. the child's physiotherapist) to view at the end of the session out of interest and for discussion. This is possible even with only 1 member of lab staff available to perform all tasks during the data collection session.

In the last year I have set-up an in-house video vector system using CODA to generate the ground reaction force vector. This system is currently being used clinically to assess orthoses in children of all ages, and for a couple of new research projects.

The lab has 3 main areas of activity: clinical, teaching and research. Clinically the lab provides a gait analysis service to the Nottinghamshire and surrounding area, accepting referrals from locally agreed referrers without charge, and from other referral sources with funding. In the last year, a weekly gait and orthotic assessment service has also been set-up in conjunction with the community paediatric physiotherapists, using the video vector system to assess and fine-tune orthoses and footwear.

From a teaching perspective the lab is regularly used during the undergraduate BSc physiotherapy programme for the teaching of normal movement, analysis of human movement (from gait to jumping and running), normal and pathological gait, biomechanics, EMG and the use of equipment to assess human function / performance. The students appear to enjoy this different and interesting environment, with the chance to use equipment not necessarily available on placement or even after graduation once in employment. Teaching also takes place at a postgraduate level to Masters students, external courses, as well as in teaching as part of CPD to clinical staff and colleagues.

During the final year of the course the students undertake a research project, with the lab being a popular setting for data collection. Increasingly I am recommending the students use the CODA system due to its diversity of application and accuracy of data collection. With outcomes including force, kinematics, gait spatio-temporal parameters and EMG activity able to be collected simultaneously the system is very adaptable, and examples of student research projects using CODA include:

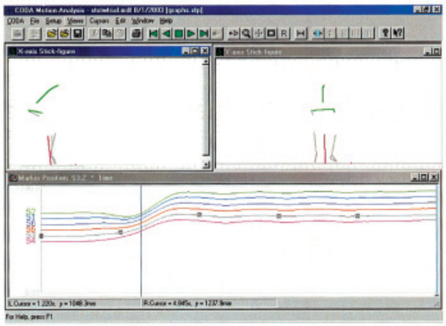

Fig 2. Simple model of shank, pelvis and spine for assessment of spinal movement, showing movement traces of spinal levels during sit-to-stand.

The effect of massage on EMG activity of the upper trapezius muscles.
The effect of taping on VMO / VL activity during step-up – using the force plate to determine onset of step-up **(see Fig 1)**
The effect of exercise on peroneal latency - again using a trap door on the force plate to determine onset of activity, along with EMG readings of the peronei to determine onset timing of muscle activation.
The effect of ankle taping on vertical jump time (and therefore height) and ankle range of motion – using the force plates again to determine onset and completion of the jump, and a simple lower limb model to calculate ankle range of motion in the saggital plane.
At present CODA is the only system we have that can integrate force, EMG and motion allowing EMG activity to be directly linked to function.

The lab is currently increasing its research profile both by staff within the division undertaking research, and in collaboration with clinical colleagues from the local trusts. The areas of research within the lab broadly fall into the category of analysis of human performance but range from assessment of cervical mobilisation skill, to gait analysis in various forms, to assessment of balance within the arthritic population, and of strength and endurance in oncology patients.

Along with increasing experience of using the system, the diversity of research using CODA is also increasing. As well as a basic gait study assessing the normal kinematics of children using CODA, we have started to use the system to assess non-gait activities. A new study in its infancy at the moment is an investigation into the effect of spinal bracing on spinal movement and function in the osteoporotic population. The CODA system is being used to model the spine with and without the brace in situ to allow this analysis to take place. **(see Fig 2)**

As the motion analysis systems become more complex and adaptable, more complex and in-depth studies are being able to be undertaken into aspects of normal movement yet to be studied, or the effect of therapeutic intervention on very specific functioning of the human body. The use of motion analysis has definitely stretched my mind in many different directions since I started working within this field, and I am sure it will continue to do so given the ever increasing potential and scope of motion analysis work.

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