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Investigating Balance and Stability: A Review

Lexyne McNealy Jackson, M.S.

As individuals age, control of the neuromuscular system tends to diminish and elderly populations are well-known to have a high incidence of falling. Maintaining balance is even more critical for populations with a lower limb amputation, where incidences of falls may be associated with increased levels of instability. With more proximal levels of amputation, the control of balance may be reduced due to the absence of proprioceptive feedback in the foot and joint control at the ankle and knee for persons with transtibial and transfemoral amputations, respectively. Researchers and clinicians must understand the mechanisms of balance in order to design and develop components that increase function in the prosthetic limb. However, no standard measurements of balance control have been established, so investigators tend to discuss balance and stability in terms of descriptive, indirect measures.

The purpose of this review is to examine some typical methods that researchers use to evaluate balance and postural stability, and to highlight the need for further investigation of balance in persons with lower limb amputations.

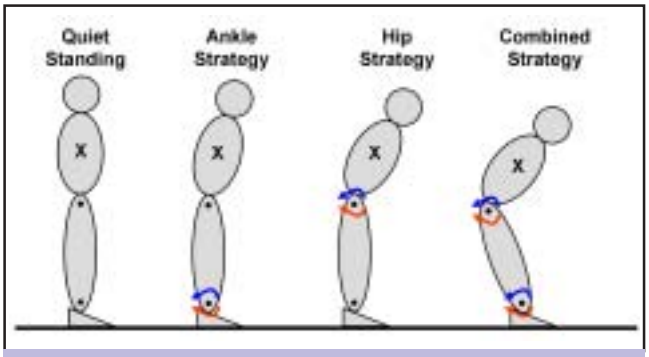

Figure 1: The body center of mass (BCOM) of an able-bodied subject is displaced from its equilibrium position during quiet standing in each of the examples shown above. Moments about the ankle and hip joints are used to return the BCOM to equilibrium. BCOM is denoted by the "X", while ankle and hip joints are denoted by the filled black circles [•]. Counterclockwise and clockwise arrows represent extension and flexion moments, respectively, about the joints. Illustration modified from [1].

Strategies for Static and Dynamic Balance

Static and dynamic balance as discussed here refers to the ability to remain upright without falling during standing and walking, respectively. Additionally, it is important to note that balance and stability are broad terms used to describe the state of equilibrium of a system or body. The means by which a system maintains its equilibrium in three-dimensional space can be examined by introducing a perturbation or disturbance into the system. For example, testing the mechanisms of balance control in a human subject may entail introducing a perturbation beneath the floor on which the person stands and observing how the individual returns to his/her original equilibrium position.

Ankle and hip strategies are the two primary methods able-bodied individuals use to control static and dynamic balance and upright posture (**Figure 1**) [1]. The type of strategy used in static balance is largely dependent on the magnitude and direction of the perturbation. Recovery from a perturbation during dynamic balance includes the additional requirement of maintaining forward (or backward) progression. In either case, large perturbations are generally controlled by rotating the trunk about the hip joint to return the body center of mass (BCOM) to an equilibrium position, while smaller perturbations typically are regulated via rotation about the ankle joint [2]. Additionally, a combined ankle and hip strategy can be used to offset a large perturbation.

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Individuals with amputations may lack the necessary feedback and control in the amputated limb to aid in static and dynamic balance. Therefore, they must use alternative means for control.

Active Control/Stabilization of Lateral Balance

Bauby and Kuo [3] conducted one of the earliest investigations of balance control in the frontal plane, or lateral balance. This study was the first to suggest that balance in able-bodied individuals was passive in the sagittal plane, while lateral balance was actively managed by the central nervous system (CNS). Lateral balance has been suggested as a contributing factor in the incidence of falling in the elderly [4]. Examining lateral balance also may elucidate precursors of falling in persons with lower limb amputations. However, investigations of active control of lateral balance in persons with amputations have received little attention in current literature.

BCOM/COP

Researchers also have investigated how balance is related to BCOM and the center of pressure (COP). The BCOM represents the equivalent point of the total body mass of each body segment in space, while the COP represents the equivalent point of all pressures over the surface of contact with the ground [5]. The BCOM and COP were found to be closely regulated by the CNS to control total body balance [2] and have been linked to the activity of the muscles in the ankle joint [5]. While small displacements from the BCOM and COP equilibria may indicate a higher level of stability and balance control (**Figure 2**), this method has yet to be determined as an accurate indicator of balance.

Figure 2: While an able-bodied subject stands as motionless as possible on a force platform, oscillations of the body center of mass (BCOM) and center of pressure (COP) about a relative equilibrium position—in this example, the mean positions of the BCOM and COP—can be observed. Both BCOM and COP show small displacements about the equilibrium point. (Data are courtesy of the VA Chicago Motion Analysis Research Laboratory.)

Perturbations of the Nonlinear Dynamical System: Human Locomotion

Recently, non-traditional means have been used to study the dynamics of human locomotion. In particular, nonlinear dynamics or chaos theory have been applied to investigate local dynamic *system* stability—not to be confused with *postural* stability. England and Granata [6] determined that walking speed indirectly influences dynamic stability due to increased effort by the CNS to decrease kinematic disturbances at the higher speeds. Additionally, results from a recent study revealed that individuals who are prone to falling decrease their walking speed in order to increase their dynamic stability [7]. This method of analysis has been used primarily on able-bodied subjects, and has not been used for the study of persons with amputations.

Summary

Static and dynamic balance generally is examined using a variety of methods, some of which are presented here. However, these analyses have been limited largely to able-bodied populations. As of 2005 in the United States, an estimated 623,000 people had a major lower limb amputation, including transfemoral, transtibial, and foot amputations [8]. It is critical to examine balance among populations of persons with a lower limb amputation, since prosthetic components that are designed to allow rotation about the ankle joint may inadvertently decrease stability [1, 9].

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Tatjana Mauch Remembered

By R. J. Garrick, Ph.D.

Mrs. **Tatjana (née Schmitt) Mauch** was born on July 1, 1919 in Vienna, Austria and died on April 14, 2008 in Centerville, OH. Mrs. Mauch was director and president of Mauch Laboratories after the death of her husband, the renowned German engineer, **Hans Mauch**, whom she married in 1948. Generous and open-minded, Mrs. Mauch contributed two major endowments to the **Northwestern University Prosthetics Research Laboratory** (NUPRL). These endowments have supported many research activities in prosthetics and orthotics.

Mrs. **Tatjana Mauch** (left) attended the ISPO 7th World Congress (Chicago) as an invited Special Guest. She is pictured with **Dudley S. Childress**, Ph.D. (center), and Dr. **René Baumgartner** (right).

Hans Mauch had been a civilian engineer at the German Air Ministry from 1935-1939 and later acted as a consulting engineer from his own company. In 1946 Hans Mauch was recruited as a "paperclip scientist" and moved to Dayton, OH, where he was employed at the Aeromedical Laboratory of the Wright Air Force Development Center. Mr. Mauch was a prolific inventor, holding more than eighty patents on innovations that contributed to many fields, including aviation and medicine. Mr. Mauch is recognized for developing the "Hydraulic Knee Control System" (Mauch SNS) for above the knee amputation.

"The Mauch swing control provided programmed resistance that automatically varies with knee angle and walking speed, as well as independent adjustment of resistance to flexion and extension. The stance phase control always allows extension, but automatically imposes a high but adjustable resistance to knee flexion except after a brief application of a hyperextension moment, normally after the heel leaves the ground. These knee control features are superior to other brakes and locks that have been disclosed in literature and patent applications here and abroad for well over a century." (Excerpt from "Hans Adolph Mauch," *Memorial Tributes*, National Academy of Engineering, Volume 3, pp 258-265.)

Variants of this system are in use today and provide a voluntary control of swing and stance phase movement. He was elected to the National Academy of Engineering in 1973. After the death of Mr. Mauch in 1984, Mrs. Mauch continued to support research in prosthetics engineering.

NUPRL's **Brian Ruhe**, M.S., who met Mrs. Mauch at her home in Centerville, OH, recalls her as a gracious and enthusiastic person. *"She was deeply interested in continuing her husband's work helping people who had lost limbs."* Vigorous and energetic, she served as docent at the Dayton Art Institute, volunteered with Catholic Social Services, and was an accomplished ballroom dancer. In 1992 Mrs. Mauch was invited as a Special Guest to the ISPO 7th World Congress in Chicago. NUPRL's **Dudley S. Childress**, Ph.D., remembers dancing with her at that event and reported that she danced "as lightly as a feather."

A generous philanthropist, Mrs. Mauch supported research in prosthetics engineering, including products developed at NUPRL. While Mrs. Mauch's kindness and generosity as a great benefactress to NUPRL and NURERC will be missed, her legacy will endure in the work of this laboratory.

Joann Williams Renews Link with NURERC

By R. J. Garrick, Ph.D.

Ms. **Joann Williams**, a Soldier Family Management Specialist and contractor from Serco Inc., visited NURERC and NUPOC on April 22, 2008. Currently, Ms. Williams works in association with the U.S. Army Wounded Warrior Program (AW2); however, from 1974 to 1975 she worked as an assistant at the Northwestern University Prosthetics Research Laboratory (NUPRL). She returned to the laboratory to learn about state of the art prostheses; renew her acquaintance with NUPRL's Director Emeritus **Dudley S. Childress**, Ph.D.; and meet Director of NUPRL, **Steven A. Gard**, Ph.D.

(From left to right) **Steven A. Gard**, Ph.D., Director of NURERC, Ms. **Joann Williams** and **Dudley S. Childress**, Ph.D., Director Emeritus of NURERC.

As an AW2 Soldier Family Management Specialist, Ms. Williams interfaces with the VA Medical Center in Danville, IL, to provide personalized transition for severely wounded soldiers and their families. Ms. Williams' current case load consists of 15 soldiers and veterans in different stages of recovery.

Acting on the motto, *"We will never leave a fallen comrade,"* AW2 extends an array of social, educational, medical, financial, legal and other support services to severely injured soldiers, veterans and their families. From October 2007 through July 5, 2008, more than 32,500 military personnel have been wounded in the "Global War on Terror." (See this website for updated military casualty statistics: http://siadapp.dmdc.osd.mil/personnel/CASUALTY/gwot_component.pdf). Among the wounded, about 2,500 military personnel have returned with critical disabilities and are being served by AW2.

AW2 assists severely wounded soldiers to become self-sufficient, contributing members of their communities, offering services that include life coaches, family assistants, financial and military benefits, as well as legal and educational guidance. Veterans who are eligible for these services are those who return to civilian life from Iraq and Afghanistan with a thirty percent or greater disability rating from multiple injuries that include amputation, burns, blindness, deafness, traumatic brain injury (TBI), post traumatic stress disorder (PTSD), and spinal cord injury (SCI). Some soldiers may recover enough function to return to active or reserve service, while others require AW2 support for the rest of their lives.

Dudley Childress, Ph.D., **Steven A. Gard**, Ph.D., and NUPOC's **Mark Edwards**, MHPE, CP, summarized recent developments in prosthetics engineering and showed Ms. Williams a variety of lower limb prostheses that ranged from prototypes still in development to the newly available PROPRIO FOOT® by Ossur. Ms. Williams is developing new knowledge about prosthetics and orthotics, which she plans to use in future services for severely disabled veterans and their families. (To learn more about AW2 or to hire a Wounded Warrior, see www.aw2portal.com.)

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NUCATS' John Linehan, Ph.D., Visits NURERC

By R. J. Garrick, Ph.D.

John Linehan, Ph.D.

John H. Linehan, Ph.D., professor of biomedical engineering and Director of the Center for Translational Innovation (CTI) under the aegis of Northwestern University Clinical and Translational Sciences (NUCATS), visited NURERC on Tuesday, April 8, 2008. Dr. Linehan is prominent in the field of biomedical engineering (BME), particularly in the areas of leadership development, innovation design, and BME education. Dr. Linehan has developed a comprehensive model of the medical device development process that continues from discovery through concept feasibility, risk analysis, regulatory approval, manufacture, launch of product and device improvement.

An early proponent of BME innovation, Dr. Linehan became internationally known for his research in pulmonary mechanics and physiology. A proponent of BME innovation, he organized the Biomedical Engineering-Innovation, Design, and Entrepreneurship Alliance (BME-IDEA). From 1998 to 2005 he was Vice President of the Whitaker Foundation where he managed educational grant programs that developed BME departments at universities across the USA. Since 2005, he is Consulting Professor and Strategic Advisor of Bioengineering at Stanford University, and Executive Editor of www.bmesource.org, an open-source Web portal in biomedical engineering. Dr. Linehan was at Marquette University in Milwaukee, WI, from 1989 to 1998 where he was the founding chair and Rose Eannelli-Bagozzi Professor of Biomedical Engineering.

Currently Dr. Linehan directs the Center for Translational Innovation, one of the five centers in the NUCATS Institute. NUCATS is part of a national effort that is funded by The National Institutes of Health (NIH) to promote interdisciplinary research in the biomedical sciences and *"to lower artificial barriers that divide biomedical researchers and impede scientific progress"* (See www.ncrr.nih.gov/biomedical_technology). Seeking to promote research that will provide better medical preventions, diagnoses, treatments and cures for human diseases, NUCATS matches interdisciplinary research interests and uses the combined resources of Northwestern University and its clinical affiliates to transfer new medical devices to commercial and clinical use.

John Linehan, Ph.D. (left), holds a single unit SquirtShape socket and pylon fused to a Shape&Roll Prosthetic foot as **Joshua Rolock**, Ph.D. (right), explains the potential of integrated pylons.

Within the CTI at NUCATS, Dr. Linehan oversees three programs: 1) Research Discovery Program; 2) Translational Research Incubator Program; and 3) Technology Development Program. CTI promotes translational research by identifying, developing and marketing new medical devices. After matching a clinical need with commercial opportunities, teams of specialized consultants accompany a new medical device through the complex maze of financial review, risk assessment, patent filings, regulatory approval, and through the stages of manufacture, marketing, sale, and product improvement. CTI discovers innovative opportunities through interdisciplinary exchange, such as the CTI-hosted brainstorming sessions between clinical needs and engineering; and seminars attended by Northwestern Memorial Hospital neurosurgeons and McCormick Center engineering faculty. (For more information, see www.nucats.northwestern.edu.)

Shown from left to right are **Dudley S. Childress**, Ph.D., **John Linehan**, Ph.D., **Kathy Waldera**, M.S., who is a Research Engineer at NURERC and a former student of Dr. Linehan, and **Steven A. Gard**, Ph.D.

NUPOC Students Visit NURERC

R. J. Garrick, Ph.D.

With a mere three weeks remaining before they complete the clinical portion of their training, NUPOC prosthetics and orthotics students toured the **Prosthetics Research Laboratory** on June 9, 2008. Students visited four learning stations where they learned about prosthetics and orthotics research that is conducted at NURERC. **Dudley S. Childress**, Ph.D., conducted an overview of upper limb prostheses; **Kerice Tucker**, Research Engineer, explained the application of SquirtShape and other CAD/CAM technology in prosthetics; **Liz Klodd**, graduate student, reviewed the development and fabrication of the Shape&Roll Prosthetic Foot for use in developing countries; and **Stefania Fatone**, Ph.D., **Brian Ruhe**, M.S., and **Rebecca Stine**, M.S., demonstrated technology for the analysis of gait and motion.

Mariasol Roberts

People come from diverse backgrounds and regions to attend the NUPOC programs. This term the southwest is represented by prosthetics participants from New Mexico and Texas. **Mariasol Roberts** hails from New Mexico. She has two daughters and is pregnant with her third child. *"I've missed my daughters so much during these two months; but, seeing me reach my goals will empower them to achieve their own goals and dreams."* With a background in Molecular Biophysics and Biochemistry from Yale, two years at medical school, and subsequent experience as a prosthetics technician at a VA facility, Mariasol discovered that prosthetics offers an ideal opportunity to blend her interests. She applies her engineering knowledge to hands-on fabrication processes and enjoys using her clinical skills for rewarding interaction with her clients. She looks forward to her future as a prosthetist in New Mexico.

Jesse J. Rettele is from San Antonio, TX. Jesse began working in the prosthetics field while still in high school. Now, at the age of 30, he already has twelve years' experience working in the technical side of prosthetics. Attending the NUPOC course fulfills a dream Jesse has had since he began assisting P&O practitioners, many of whom also were NUPOC graduates. *"I love what I do and each day presents new challenges. I decided that prosthetics and orthotics would be my career choice when I was invited to see a young boy with congenital amelia who was fit with a set of bilateral prostheses that I had fabricated. When he stood up and walked for the first time, his whole family erupted in tears of joy. That's when I realized that the field of prosthetics is where I belong."* Jesse is eager to return to San Antonio where he will practice as a prosthetist.

Jesse Rettele

Originally from New York, **Peter J. O'Brien** now calls Waco, TX, home, where he lives with his wife and daughter. He is a former U. S. Coast Guardsman. Peter has a personal as well as a professional perspective about the importance of fitting and fabricating comfortable, well-aligned prostheses. Less than two years ago, Peter experienced a transfemoral amputation due to cancer. His experience brought the field of prosthetics into sharp focus as he recovered and learned to use his C-Leg® Microprocessor Knee from Otto Bock. *"I pestered my prosthetic team constantly to learn how I could be a more proficient ambulator. Very quickly I became interested in prosthetics as a profession and began working as a prosthetic technician. I completed the prerequisites for the NUPOC program at Baylor and here I am with only three weeks before I finish this program."* Peter looks forward to honing his skills in a prosthetics residency near his home.

Peter O'Brien

Through determination, focused effort, and intensive study, these NUPOC students and their cohort have acquired the new skills and knowledge that they will parlay into rewarding, professional careers in prosthetics.

Mark L. Edwards to Step Down as Director of Prosthetics Education

R. J. Garrick, Ph.D.

Mark L. Edwards, MHPE, CP, will leave the Northwestern University Prosthetic-Orthotic Center (NUPOC) in August to accept a position with Otto Bock Healthcare.

From 1992 Mr. Edwards has served as NUPOC's Director of Prosthetics Education. Trained in prosthetics in 1983 and certified in 1985, he also trained in orthotics in 1990. Mr. Edwards began working at NUPOC with a dual appointment in the Department of Physical Medicine at Northwestern University's Feinberg School of Medicine. He has been a consulting prosthetist for the Rehabilitation Institute of Chicago, the Northwestern University Prosthetics Research Laboratory, and the Center for International Rehabilitation (CIR). He collaborated on CIR's distance education program for Central America and the Balkans to train Category II prosthetists and in July Mr. Edwards will travel to Bosnia where he will assist in that training.

Mark L. Edwards

Active in professional societies, Mr. Edwards has served as President of the Midwest Chapter of the American Academy of Orthotists and Prosthetists (AAOP); Chair of the National Association of Prosthetic and Orthotic Educators (NAPOE); and Commissioner of the National Commission on Orthotics and Prosthetics Education (NCOPE). In 1997 he served as Commissioner of the National Commission on Orthotics and Prosthetics Education (NCOPE). From 1998 through 2001 Mr. Edwards chaired the Lower Limb Prosthetics Society at AAOP. Mr. Edwards is respected as an enthusiastic and committed educator, and in 1996 the American Academy of Orthotists and Prosthetists recognized him with their Outstanding Educator Award.

Well liked by his colleagues and students, he will be missed. NURERC wishes Mr. Edwards continued success in his future endeavors.

NURERC NEWS

Meetings:

Joshua S. Rolock, Ph.D., participated as a reviewer at the NIH Musculoskeletal Rehabilitation Sciences (MRS) Study Section, held in Bethesda, MD, March 6-7, 2008.

Rebecca Stine, M.S., attended the annual meeting of the Gait and Clinical Movement Analysis Society in Richmond, VA, from April 2-5, 2008. The meeting focus was "The Battlefield and Beyond: Fusing Technology with Function."

Dudley Childress, Ph.D., attended a VA National Research Advisory Council (NRAC) meeting in Washington, D.C., on April 14, 2008.

Craig Heckathorne, M.Sc., attended the 32nd Annual Great Lakes Biomedical Conference in Racine, WI, on April 18, 2008. The meeting focus was "The Bionic Arms Race: Advances in Neural-Controlled Prostheses."

Steven A. Gard, Ph.D., and Stefania Fatone, Ph.D., recently attended an Outcomes Initiative Committee Meeting, held in Fairfax, VA, on April 25, 2008. This was part of an ongoing series of meetings sponsored by the American Academy of Orthotists and Prosthetists (AAOP) and the American Orthotic and Prosthetic Association (AOPA).

William Brett (BJ) Johnson, M.S., successfully defended his Master's thesis, "Preliminary Quantitative Gait Analysis of Reciprocating Gait Orthosis (RGO) Users," in Biomedical Engineering on March 13, 2008.

B. J. Johnson, M.S.

RGO ambulators bear much of their body weight through the arms, possibly contributing to high energy expenditure. His study observed that hip extension at the beginning of the swing phase seems to counter the forward advancement of the swing leg, while poorly conserved mechanical energy at the trunk may increase energy expenditure. His work suggested that deceleration of the body center of mass during the second half of swing also may cause poor energy conservation. Congratulations!

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New Faces: NURERC Welcomes Charles C. Wang

By R. J. Garrick, Ph.D.

Charles C. Wang has joined NURERC as a two-year Master of Science graduate student in biomedical engineering. He is working with **Andrew Hansen, Ph.D**., on a study of able-bodied walkers, comparing their energy expenditure and roll-over shapes while walking at different speeds and with different rocker bases. Charles completed his undergraduate work at Duke University where he studied biomedical and electrical engineering.

Charles C. Wang

Charles has lived in several countries. His international experience heightened his awareness of disability and contributed to his keen interest in using his engineering skills as an effective response to global problems. While at Duke University, Charles participated in Engineers without Borders (EWB) and worked on philanthropic outreach projects such as designing mechanical aerators for Indonesian shrimp hatcheries and building play areas for children with physical disabilities. At Northwestern University he assists the bioengineering problem-solving curriculum, **Get-a-Grip!** (See *Capabilities* Volume 16, Number 2, pages 4-5.) His future goals include continuing to use his engineering knowledge to improve healthcare in disadvantaged areas.

In addition to his work in engineering, Charles plays basketball on an intramural team and enjoys attending Chicago Bulls games. Also, he is an avid cinemaphile and traveler.