



College of Engineering

12th Annual

Biomechanics Research Symposium

May 8, 2015

Center for Biomechanical Engineering Research

201 Spencer Lab | Newark, Delaware 19716 | www.cber.udel.edu

Welcome students, faculty and friends!

Welcome you to the 12th annual Biomechanics Research Symposium – We hope you will enjoy learning about the breadth and depth of the Biomechanics and Biomechanical Engineering research being conducted at the University of Delaware by the students, faculty and research professionals.

This year, you will see talks and posters on subjects as varied as human motion after injury or stroke, the mechanics of musculoskeletal tissues, the development of devices and technologies for correcting and measuring human motion and the transport and effects of drug therapies on cartilage and bone. We are pleased to have Dr. Dawn Elliott, Director of the UD Biomedical Engineering Program, give our keynote address at this year's symposium. Dr. Elliott's lecture is titled, "Studying tissue biomechanics is like taking apart a cat to see how it works, you get a non-working cat."

As we continue to celebrate the interdisciplinary and collaborative spirit upon which CBER was founded, I welcome your advice and participation in the future of the center, as we navigate through the new challenges ahead. Thanks to the Delaware Rehabilitation Institute, for their generous sponsorship of this year's student awards, and a special thank you to all the participants, presenters and listeners, in this 12th annual CBER day, Biomechanics Research Symposium.



ACKNOWLEDGEMENTS

ORGANIZING COMMITTEE MEMBERS

Michael H. Santare

Elaine Nelson

STUDENT COMMITTEE MEMBERS

Andrea Di Trani

Paula-Marie Ferrara

Danielle Gerstman

Chris Henderson

Kathleen Madara

Jackie Palmer

Alexander Razzook

Aaron Struminger

All student awards are sponsored by the Delaware Rehabilitation Institute

Keynote Lecture



Dawn M. Elliott, PhD

Dawn Elliott is a professor and director of Biomedical Engineering at the University of Delaware. Prior to joining Delaware in 2011, she spent 12 years in the University of Pennsylvania's Departments of Orthopaedic Surgery and Bioengineering, where she was promoted to full professor. Dr. Elliott earned a doctoral degree in biomedical engineering from Duke University, a master's degree in engineering mechanics from the University of Cincinnati, and a bachelor's degree in mechanical engineering from the University of Michigan. Dr. Elliott is a leader in the field of musculoskeletal biomechanics. She investigates the changes that occur in load-bearing fibrous tissues, such as disc, meniscus, and tendon, during development, with degeneration and injury, and

following therapeutic interventions. Her multi-scale approach, from the entire joint-level, to the tissue-scale, and to the micro-scale, integrates mechanical testing, mathematical modeling, and multi-modal imaging. Dr. Elliott has published over 140 peer-reviewed papers, has an h-index of 34, and has been cited in over 2,600 articles without self-citations (source: ISI Web of Science 3/2015). In 2015 she was awarded the American Society of Mechanical Engineers (ASME) Van C. Mow Medal for significant contributions to the field of bioengineering.

Dr. Elliott has been an outstanding teacher, mentor, and contributor to the professions of biomedical engineering and orthopaedics. In 2015 she was awarded the inaugural Outstanding Achievement in Mentoring Award from the Orthopaedic Research Society. Dr. Elliott is a Fellow of the American Institute for Medical and Biological Engineering (AIMBE) and of ASME. She currently serves on the executive boards of the International Society for the Study of Lumbar Spine (ISSLS), the Council of Chairs of Biomedical Engineering, the Biomedical Engineering Society (BMES), and on the board of directors of The Perry Initiative, a non-profit organization dedicated to increasing role of women in engineering and medicine. Dawn was a member of the NIH Study Section Musculoskeletal Tissue Engineering and has served on numerous NIH and other review panels.

Schedule of the Day

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PODIUM PRESENTATIONS

Session 1

1 ADAPTATIONS IN LOWER EXTREMITY WORK DUE TO CHANGES IN WALKING SPEED

Anahid Ebrahimi, Saryn R. Goldberg¹, Steven J. Stanhope

¹ HOFSTRA UNIVERSITY

The objective of this study was to understand the work adaptations of all the lower extremity limb constituents (ankle, knee, hip, and distal foot) that occur in order to increase walking speed. Eight unimpaired adult subjects walked on an instrumented split-belt treadmill at three height-normalized velocities (0.4, 0.6, and 0.8 statures/s). Motion capture and force plate data were collected and input into Visual3D software to calculate 6 degree-of-freedom powers of each constituent. Integrating over the positive or negative portions of the respective constituent power curves during stance and swing phases provided positive or negative constituent work values. Net constituent work was the sum of the positive and negative constituent work for each constituent. Net limb work was the sum of all net constituent work values. Absolute limb work was the sum of the positive limb work and absolute value of the negative limb work. Relative constituent work was the absolute value of each constituent's work divided by the absolute limb work. All work values were normalized by body mass and stride length. In stance, net ankle work and net distal foot work significantly increased, while net hip work significantly decreased with speed ($p < 0.05$). In addition, as speed increased, the knee and hip generated less relative positive work in stance. Net limb work and absolute limb work did not significantly differ with faster walking. We conclude that while net limb work did not change significantly with speed, net constituent work did change (except at the knee). Relative constituent work helps identify the extent of individual joint adaptations and where in the gait cycle they occur to enable unimpaired persons to walk at faster speeds.

2 IN SEARCH OF MENISCUS CRACK PROPAGATION

John M. Peloquin¹ and Dawn M. Elliott

¹ UNIVERSITY OF PENNSYLVANIA, PHILADELPHIA

Knee meniscus cracks are a precursor for osteoarthritis, which is debilitating and difficult to treat. Little is known about how or why cracks in meniscus (or other fibrous tissues) grow. Studies have been stymied by difficulty reproducing crack propagation in the lab. This difficulty may be caused by the use of single edge notch test (SENT) specimens. Finite element analysis (FEA) results that we presented at the 10th CBER symposium predicted that center cracks are more likely to propagate. In the present study, we physically tested both configurations. Cracked specimens were compared with crack-free controls using peak stress, peak stretch, yield stress, and tangent modulus. Digital image correlation was used to measure crack-associated strain fields. Surprisingly, although the FEA predicted the center crack specimens to have the most severe stress concentration, its stress and stretch metrics were very similar to crack-free controls. Also unexpectedly, SENT specimens reached their peak stress values at greater peak stretch than the crack-free controls; the outer meniscus (the uncracked side) may be stronger than the inner meniscus. Rupture began at sites of severe shear strain and propagated along inter-fascicular boundaries. Although the cracks did not grow, strain concentrations did form at the crack tips. In vivo, these crack-associated strain concentrations may disrupt tissue homeostasis or cause fatigue failure. Together with the FEA, this study builds towards the goal of being able to provide a prognosis for meniscus cracks and thereby guide patient treatment.

3 HOW DO SOCCER PLAYERS AFTER ACLR COMPARE TO NORMATIVE SINGLE-LEGGED HOP DATA?

A. Arundale, E. Wellsandt, Lynn Snyder-Mackler

Introduction: The purpose of this study was to compare single-legged hop test scores of soccer players at 6, 12, and 24 months after ACLR to the published normative values.

Methods: At 6, 12, and 24 months following unilateral ACLR, 37 soccer players were assessed using the single hop (SHP), cross-over hop (XHP), and triple hop for distance (THP), and six meter timed hop (6mHP). Athletes were categorized; high school males and females, and college males and females. Limb symmetry (LSI) was calculated and each group was sub-divided based on achievement of $\geq 90\%$ LSI. Chi squared tests were used to assess if there were differences between groups in number of players who achieved $\geq 90\%$ LSI. Median hop scores were calculated for each subgroup and compared to the normative data.

Results: There were no significant differences between groups in number of athletes with $\geq 90\%$ LSI (6 months $p=0.82$, 12 months $p=0.47$, 24 months $p=0.506$). Of those with $\geq 90\%$ LSI college males and females and high school males were bilaterally below the normative value for SHP, XHP, and THP at all three time points, with the exception of high school males uninvolved XHP at 6 months. High school females were above the normative value for SHP, XHP, and THP at 12 and 24 months on their involved limb. All groups had 6mHP scores faster than the normative values except college females at 12 months and college males at all time points.

Discussion: While not all athletes will reach normative values, the gross lack of achievement could indicate risk for subsequent injury. Further, because both limbs fall below the normative range for many of these athletes bilateral strengthening and neuromuscular training may be beneficial.

4 THE RELATIVE CONTRIBUTION OF TRAILING LIMB ANGLE AND ANKLE MOMENT TO CHANGES IN PROPULSIVE FORCE DURING WALKING IN INDIVIDUALS POSTSTROKE

HaoYuan Hsiao¹, Brian A. Knarr², Jill S. Higginson^{1,3}, Stuart A. Binder-Macleod^{1,4}

¹ BIOMECHANICS AND MOVEMENT SCIENCE PROGRAM

² DELAWARE REHABILITATION INSTITUTE

³ DEPARTMENT OF MECHANICAL ENGINEERING

⁴ DEPARTMENT OF PHYSICAL THERAPY

Current gait rehabilitation for individuals poststroke focuses on increasing gait velocity because walking speed is a powerful indicator of function after stroke. A major factor required for translating the body forward during gait is the ability to generate propulsive force. Previous studies have identified that ankle plantar flexor muscle strength and trailing limb angle (TLA) are critical factors for generating propulsive force. Using a biomechanical-based model, our lab reported that the ratio of the contribution from TLA versus ankle moment to increases in propulsion during speed modulation is approximately 2:1 in able-bodied individuals and 4:1 in the paretic limb for stroke survivors. The primary purpose of this study was to quantify the relative contribution of ankle moment and TLA to changes in propulsive force following a targeted gait intervention. Twenty-eight participants completed three training sessions a week for 12 weeks. Data were collected when participants walked at their self-selected and fastest walking speeds on a treadmill both pre and post intervention. After training, the ratio of the contribution from TLA versus ankle moment to changes in walking speed within a session is 3:1. In addition, from pre to post training, the ratio of the contribution from TLA versus ankle moment to changes in walking speed is 2.3:1 at self-selected walking speed and 1.6:1 at fastest walking speed. Our findings suggest that following gait training, the mechanism used to increase propulsion more closely matched that of able-bodied individuals. Future research on determining the best strategy to increase propulsion is needed.

5 A CROSS-SECTIONAL AGE-WISE ASSESSMENT OF MORPHOLOGY AND BONE FORMATION IN PERLECAN-DEFICIENT MICE

Ashutosh Parajuli, Dave Gu, Xiaohan Lai, Zhushui Zhang, Catherine Kirn-Safran, Liyun Wang

Introduction: Perlecan, a large heparan sulfate proteoglycan, is typically found in the cartilage extracellular matrix and basement membranes of heart, kidney and skeletal muscles. Perlecan deficiency results in a number of skeletal abnormalities including Schwartz Jampel syndrome (SJS). Perlecan is known to prevent mineralization during chondrogenesis and regulate osteogenic processes during endochondral ossification. Using a perlecan deficient mouse mimicking SJS (C1532Y neo mice), we characterized the perlecan-deficient bone's phenotype at various stages of growth and development.

Methods: Two groups of male mice were used: C57BL/6J and perlecan-deficient Hypo mice. Animals were sacrificed at 5 different ages. The right femora were harvested & imaged using Scanco MicroCT 35 (Scanco Medical AG, Bruttisellen, Switzerland). The midshafts of tibiae were fixed in formalin, embedded in plastics, sectioned, polished, and imaged using OsteoMeasures[®]. All data are presented as mean \pm standard deviation.

Results: The Hypo mice had significantly smaller body weight and shorter femoral length. Except for a lower Ct.BA/TA shown in 8-week-old Hypo, the femoral mid-diaphysis showed few differences. Hypo trabecular bone showed significant lower bone volume fraction at most ages examined and declined much faster. Dynamic bone labels showed higher endosteal activity than the periosteal.

Discussion: We characterized the bone morphology and osteoblastic bone formation in both cortical and trabecular compartments. The differences between the two genotypes were mainly found in the trabecular compartment, where Hypo mice demonstrated significant reduced bone volume fraction with fewer, thinner and sparser trabeculi.

Significance: Studying the roles of perlecan in bone development and bone adaptation will help to elucidate the molecular mechanisms for bone mechanosensing and to develop new treatments for osteoporosis.

Acknowledgements: NIH P30GM103333; RO1AR054385.

PODIUM PRESENTATIONS

Session 2

1 GAIT PATTERNS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION DIFFER WITH GRAFT TYPE

Ryan Zarzycki, David Logerstedt, Lynn Snyder-Mackler

UNIVERSITY OF DELAWARE BIOMS/PT

Introduction: After anterior cruciate ligament reconstruction (ACLR), subjects demonstrate altered movement asymmetries during gait that may increase the risk of osteoarthritis (OA) development. Graft type can influence kinematics and kinetics during gait. The purpose of this investigation was to determine if differences in gait exist between subjects undergoing ACLR with hamstring (HS) autograft and subjects with bone-patellar tendon-bone (BPTB) autograft.

Methods: Thirty-five subjects following ACLR were included in this analysis. Twenty six subjects underwent ACLR with a HS autograft, while 9 underwent ACLR with a BPTB autograft. Motion capture was performed during gait at the subject's preferred walking speed. Knee and hip joint angles and moments were calculated in all three planes of motion at initial contact (IC), peak knee flexion (PKF), and peak knee extension (PKE). A 2 x 2 analysis of variance was utilized to detect differences between limb and group.

Results: Significant group x limb interactions were found with knee adduction angle at peak knee flexion. The BPTB group had greater asymmetry resulting from a greater mean adduction angle of the uninvolved limb. There was no significant interaction with external knee flexion moment at peak knee flexion although the mean difference between limbs was greater than the minimal clinically important difference of .04 Nm/kg*m. There were no significant interactions with all other variables.

Discussion: In this analysis the BPTB group displayed greater asymmetry. The BPTB group were likely unloading their surgical knee, and compensating for this by altering their uninvolved motion in the frontal plane. Altered loading following ACLR may increase the likelihood of knee OA. Based on these findings, subjects with BPTB autograft may be more likely to develop knee OA.

2 SHOULDER MALADAPTIONS OCCUR IN 8–10 YEAR-OLD OVERHEAD ATHLETES

Aaron H. Struminger, M.A. Astolfi, K.E. Shonk, Charles B. Swanik

Context: Over two-thirds of elite swimmers and baseball players will experience shoulder pain during their competitive lifetimes. This pain can begin as early as 8 years of age and has been primarily attributed to losses in internal rotation range of motion associated with posterior capsule tightness. However, little data exist determining when range of motion changes occur or examining the underlying tissue maladaptations in overhead athletes.

Purpose: To compare adaptations in the shoulder of swimmers, baseball players, and controls aged 8–10.

Participants: Fifty-five youth athletes; 20 swimmers (years played=3.03±1.42), 15 baseball players (years played=4.93±1.67), 20 non-overhead athletes.

Main Outcome Measures: A digital inclinometer and diagnostic ultrasound were used to measure glenohumeral internal rotation, glenohumeral external rotation, posterior capsule thickness, and humeral retrotorsion (twisting) bilaterally. The dominant arm was defined as the arm used to throw a ball for maximum distance. Dependent variables were analyzed using a 2 x 3 mixed model ANOVA and Tukey post-hoc testing.

Results: Baseball players exhibited a 9.2° internal rotation loss and 18° external rotation gain on their dominant arms compared to their non-dominant arms. This range of motion difference between arms did not exist in swimmers or controls. The dominant arms of baseball players manifested with greater posterior capsular thickness (1.29±0.24mm) than the dominant arms of all other populations. Swimmers (average=1.11±0.14mm) and baseball players (average=1.21±0.19mm) also exhibited greater posterior capsular thickness than control subjects (average=1.04±0.12mm). The non-dominant arms of baseball players demonstrated less humeral retrotorsion than all other arms observed.

Conclusion: Shoulder maladaptations appear in overhead athletes after only three years of sport participation and at an age earlier than previously thought. These developmental changes may be an explanation for the early development of pain in swimmers and baseball players.

3 ASYMMETRICAL CORTICOMOTOR INPUT TO THE PLANTARFLEXORS INFLUENCES THE BIOMECHANICAL STRATEGY OF SPEED MODULATION IN INDIVIDUALS POST-STROKE

Jacqueline A. Palmer, HaoYuan Hsiao, Stuart A. Binder-MacLeod

In the presence of lost function following brain injury, one of the most common and consistent observations is that individuals develop compensation strategies and demonstrate heavy reliance on the nonparetic limb during gait. Such compensations have been shown to be related to major neuronal reconstruction and growth in the cerebral cortex, which can translate to cortical imbalances between the lesioned and nonlesioned hemisphere related to poor motor recovery. Impaired ankle power generation of the paretic limb has been identified as a significant contributor to impaired walking function and is related to gait speed at baseline. However, when individuals post-stroke are asked to increase gait speed, different biomechanical strategies are used that are independent of baseline walking function. We hypothesize that balance of corticomotor input between the paretic and nonparetic plantarflexor muscles will moderate the relationship between change in paretic ankle moment and change in gait speed. To test this hypothesis, we measured corticomotor input to the paretic and nonparetic soleus muscles and paretic ankle moment of 19 persons with hemiparesis following stroke at self-selected and fast walking conditions. Preliminary results indicate that no relationship exists between change in gait speed and change in paretic ankle moment ($r = 0.035$) ($p = 0.44$) or corticomotor asymmetry ($r = 0.122$) ($p = 0.3$), but that there is a strong relationship between change in paretic ankle moment with speed modulation and corticomotor asymmetry ($r = 0.629$) ($p < 0.01$). This provides novel evidence that asymmetrical corticomotor input to the lower extremity may underlie biomechanical compensation strategies used for gait speed modulation post-stroke. These findings have significant implications for approaches used in post-stroke rehabilitation.

4 DETAILED QUANTIFICATION OF EARLY STRUCTURAL JOINT CHANGES IN THE MURINE DESTABILIZED MEDIAL MENISCUS MODEL OF POST-TRAUMATIC OSTEOARTHRITIS

Michael A. David, Melanie K. Smith, Avery T. White, Ryan C. Locke, Christopher Price

BIOMEDICAL ENGINEERING PROGRAM

Post-traumatic osteoarthritis (PTOA), an accelerated form of OA, results from traumatic joint injury, e.g., ligament tears, and is common in active individuals. ~50% of patients experiencing a ligamentous tear will exhibit OA within 15 years. Currently, preventative treatments for PTOA are lacking, potentially due to a preclinical focus on mid-to-end-stage disease, whereas the initial precipitating changes remain largely unknown. Herein, we present a detailed quantification of structural joint changes from early through late-stage disease in a murine joint instability model of PTOA, the destabilization of the medial meniscus (DMM). Mice underwent DMM surgery in the right limbs. DMM and control joints were harvested at baseline (0-), or 3-, 7-, 14-, 28-, 56-, 84- and 112-days post-injury for histologic analysis. To assess PTOA-induced structural damage, sections spanning the medial and lateral tibial plateau and femoral condyle cartilage contact surfaces were stained with Safranin-O. Three individuals scored the cartilage damage using a semi-quantitative scoring system, depth- and width-wise as well as the degree of synovitis and osteophyte formation. We found that cartilage damage in the medial compartments of DMM joints appeared as early as 7 days post-injury and was most significant at 84 and 112 days post-injury. Furthermore, synovitis and osteophyte development in DMM joints was observed as early as 3 days post-injury. Overall, this study is the first to provide a detailed temporal analysis and early identification of macroscopic joint changes in a murine model of PTOA. These results will be used as a baseline to quantify the efficacy of novel therapeutics to prevent the initiation and progression of PTOA.

5 DETERMINING THE NONLINEAR MECHANICAL PROPERTIES OF ARTICULAR CARTILAGE FROM INDENTATION TESTING

Xingyu Chen, X. Lucas Lu

DEPARTMENT OF MECHANICAL ENGINEERING

The indentation test is widely used to determine the in situ biomechanical properties of articular cartilage. The mechanical parameters estimated from the test depend on the constitutive model adopted. Similar to most connective tissues, the solid matrix of cartilage displays different mechanical properties under tension and compression, termed tension-compression nonlinearity (TCN). In this study, cartilage was modeled as a porous elastic material with either a conewise linear elastic matrix with cubic symmetry or a solid matrix reinforced by a continuous fiber distribution. Both models are commonly used to describe the TCN of cartilage. The roles of each mechanical property in determining the indentation response of cartilage were identified by finite element simulation. Under constant loading, the equilibrium deformation of cartilage is mainly dependent on the compressive modulus, while the initial transient creep behavior is largely regulated by the tensile stiffness. More importantly, altering the permeability does not change the shape of the indentation creep curves, but introduces a parallel shift along the horizontal direction on a logarithmic time scale. Based on these findings, a highly efficient curve-fitting algorithm was designed, which can uniquely determine the three major mechanical properties of cartilage (compressive modulus, tensile modulus, and permeability) from a single indentation test. The new technique was tested on adult bovine knee cartilage and verified with results from the classic biphasic linear elastic curve-fitting program.

POSTER PRESENTATIONS

ACL

1 IS THERE A RELATIONSHIP BETWEEN NONCONTACT VERSUS CONTACT MECHANISM OF ACL RUPTURE ON FUNCTIONAL OUTCOMES FOLLOWING ACL RECONSTRUCTION?

Jacob Capin, Mathew Failla, Lynn Snyder-Mackler

BIOMECHANICS AND MOVEMENT SCIENCE PROGRAM

The majority of anterior cruciate ligament (ACL) ruptures occur through a noncontact mechanism of injury (MOI); the relationship between MOI and functional outcomes after ACLR is unknown. The purpose of this study is to investigate the inter-limb differences (i.e. involved to uninjured) in functional measures and patient-reported outcomes of athletes following ACL reconstruction (ACLR) with different MOI. We hypothesize that athletes with a noncontact MOI will demonstrate greater inter-limb functional asymmetries than athletes with a contact MOI. Sixty level I and II athletes (22.4 ± 8.23 years) following unilateral ACLR (23.0 ± 7.89 weeks) were classified as having a contact ($n=23$) or noncontact ($n=37$) MOI. Subjects underwent functional testing, including: quadriceps strength index (QI); hop testing (i.e. single, crossover, triple, and timed hop tests); knee outcome survey (KOS); and global rating score. Group mean symmetry scores were compared using t-tests with alpha set to 0.05. There were no statistically significant differences between groups in QI (noncontact: $89.6 \pm 7.91\%$ vs. contact: $94.1 \pm 9.79\%$, $p=0.059$); single ($78.5 \pm 14.54\%$ vs. $83.7 \pm 15.23\%$, $p=0.197$), crossover ($84.0 \pm 16.24\%$ vs. $89.7 \pm 11.95\%$, $p=0.139$), triple ($86.5 \pm 12.07\%$ vs. $90.2 \pm 12.55\%$, $p=0.269$), or timed ($91.7 \pm 10.02\%$ vs. $93.4 \pm 8.98\%$, $p=0.420$) hop test symmetry; KOS ($92.8 \pm 6.29\%$ vs. $93.9 \pm 5.42\%$, $p=0.518$); or global rating ($80.0 \pm 9.24\%$ vs. $77.6 \pm 10.10\%$, $p=0.351$). Athletes with different mechanisms of injury may not demonstrate different functional outcomes following ACLR based on these preliminary findings. Further research with more subjects and additional time-points is needed to investigate more fully the relationship between MOI and functional outcomes in athletes following ACLR.

2 MUSCULAR CO-CONTRACTION DURING MULTI-DIRECTIONAL GRF PRODUCTION AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

Jeffrey Chandler, Amelia Lanier, Thomas S. Buchanan

Fifty percent of those who have experienced an anterior cruciate ligament (ACL) injury will develop knee osteoarthritis (OA) within 12 years of initial injury. Co-contraction of muscles surrounding the knee has been linked to increased cartilage wear, and may be a contributing factor to OA development. Recent studies have shown increased co-contraction during gait after ACL reconstruction. This trend is also present during cutting maneuvers, which are important as they increase ACL injury risk. These maneuvers require athletes to generate multi-directional ground reaction forces (mGRFs) as they quickly change direction. Therefore, the purpose of this study was to evaluate co-contraction in healthy active young adults, those who have experienced ACL reconstruction (ACL-r), and high performance athletes during multi-directional ground reaction force (mGRF) production. For this study we recruited two healthy subjects, 2 ACL-r subjects, and two high performance athletes. Subjects stood barefoot with each foot on a single force plate and were instructed to generate force in both the AP & ML directions while electromyography of seven muscles surrounding the knee was collected. Mean activation of the quadriceps (Q), hamstrings (H), and gastrocnemii (G) muscles was calculated for all groups, along with Q-H co-contraction index (CCI). ACL reconstructed subjects exhibited increased gastrocnemii activation and Q-H CCI when compared to both healthy subjects and high performance athletes. Increased gastrocnemii activation and Q-H CCI indicate a knee stabilization strategy as subjects generate mGRFs. Interestingly, Q-H CCI was the greatest in the posterior and lateral directions, potentially indicating reduced stability in those directions. Increased co-contraction during mGRF production may contribute to the high prevalence of OA after ACL rupture. This trend is important when considering most patients return to sports requiring cutting tasks.

3 DOES MECHANISM OF INJURY AFFECT GAIT BIOMECHANICS IN ATHLETES AT RETURN TO ACTIVITY AFTER ACLR?

Mat Failla, David Logerstedt, Lynn Snyder-Mackler

Anterior cruciate ligament (ACL) injuries are more likely the result of a non-contact mechanism of injury compared to a contact injury. Non-contact injury mechanisms may be a result of faulty movement patterns in the lower extremity. The purpose of this study is to evaluate differences in gait biomechanics and mechanism of injury, prior to return to activity after ACLR. This information may help tailor patient specific rehabilitation guidelines following ACLR.

Methods: Forty-four subjects after ACLR (22.4 ± 8 weeks) were included in this study. All subjects were asked to describe their mechanism of initial injury as contact (CON) or non-contact (NC), and grouped accordingly (26 NC, 18 CON). Subjects underwent gait kinematic and kinetic testing via a three-dimensional motion capture system. Gait variables were analyzed at peak knee flexion. A 2x2 analysis of variance was used to compare gait variables between limb and group, with post-hoc t-tests to determine where differences lie.

Results: No significant interactions were seen between any of the hip or knee variables. Main effect of limb was seen for hip flexion angle ($P=.007$), knee flexion angle ($P<.001$), and knee flexion moment ($P<.001$). The NC group exceeded the minimum clinically important difference (MCID) of 3° for KFA while the CON group did not. Both groups exceeded MCID of .04 NM/KgM for KFM.

Discussion: Gait asymmetries are present regardless of mechanism of injury in athletes prior to return to activity after ACLR. Rehabilitation targeting symmetry retraining is warranted in all subjects after ACLR, although athletes with a NC mechanism of injury may have greater sagittal plane knee kinetic and kinematic asymmetry than those after contact injuries. Further research with larger samples is needed to determine if non-contact ACL injuries are more asymmetrical after surgery prior to returning to activity.

4 LOWER HOP SCORES RELATED TO GAIT ASYMMETRIES AFTER ACL INJURY

Elizabeth A. Wellsandt, A. Arundale, K. Manal, T. S. Buchanan, Lynn Snyder-Mackler

Purpose: Over 50% of individuals with anterior cruciate ligament (ACL) injuries develop knee osteoarthritis (OA) within 10–15 years of injury. Both joint biomechanics and single-legged hop scores have been linked to post-traumatic OA after ACL injury. The purpose of this study is to determine whether single-legged hop scores are related to underlying gait biomechanics early after ACL injury and reconstruction (ACLR).

Methods: Athletes with a unilateral ACL injury completed testing prior to and six months after ACLR consisting of a single-legged single hop for distance and gait analysis with surface electromyography (EMG) during self-selected walking speed. Kinetic variables of interest included external peak knee flexion moment (PFKM) and adduction moment (PKAM) (interlimb loading differences=involved-uninvolved). A patient-specific EMG-driven musculoskeletal model was used to estimate the peak medial compartment contact force (MCpk) during stance phase and its loading difference. Pearson correlations were used to evaluate the relationship of biomechanical variables with single hop scores ($p\leq 0.05$).

Results: Twenty-two patients were analyzed prior to ACLR (27.3% F, 31.6±10.6 years) and 31 patients at six months (38.7% F, 31.4±10.9 years). Prior to ACLR single hop scores (mean 79.5±14.9%) were significantly correlated to involved PFKM ($p=0.026$, $r=0.474$), involved PKAM ($p=0.045$, $r=0.431$), involved MCpk ($p=0.031$, $r=0.460$), PKFM loading difference ($p=0.035$, $r=0.451$), and MCpk loading difference ($p=0.002$, $r=0.629$). Six months after ACLR single hop scores (mean 93.3±9.7%) were significantly correlated to involved PFKM ($p=0.013$, $r=0.440$), PKAM loading difference ($p=0.006$, $r=0.485$), and MCpk loading difference ($p=0.002$, $r=0.534$), but not involved PKAM ($p=0.391$), involved MCpk ($p=0.268$), or PKFM loading difference ($p=0.056$).

Conclusions: Lower hop scores were consistently correlated with lower involved limb knee moments and contact forces and greater interlimb asymmetry prior to and six months after ACLR. Lower hop scores may be representative of joint unloading patterns previously linked to the early development of post-traumatic OA.

POSTER PRESENTATIONS

Bone, Cell and Cartilage

5 NEW APPLICATIONS AND TECHNIQUES FOR ONE AND TWO DIMENSIONAL SPATIOTEMPORAL IMAGE CORRELATION SPECTROSCOPY

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The focal plane sectioning ability of a laser scanning confocal microscope is a useful feature for directly and non-invasively imaging through the depth of a tissue. Spatiotemporal image correlation spectroscopy (STICS) utilizes this advantage to quantify fluorescent particle velocity in a user-defined scan path thus allowing *in situ* observation of solute transport and fluid flow.

Previously, we have demonstrated use of one-dimensional STICS (1-D STICS) to accurately measure particle velocity, on the order of $\mu\text{m/s}$ to m/s , in laminar flow at the center of a microfluidic channel. Recently, we have demonstrated its capability over three orders of magnitude of particle sizes (2 μm to 20 nm) and six orders of magnitude of concentrations. High spatial sensitivity has been evaluated through the measurement of vertical and horizontal velocity profiles for the case of laminar flow in a rectangular channel. We established evaluation criteria for data quality and improvement of processing algorithms. This has allowed us to implement a windowed analysis that resamples the raw data to determine fluctuations in the velocity at a location over time. We have demonstrated the utility of this windowed analysis by characterizing pulsatile flow in a rectangular channel.

Additionally, we have explored bioengineering applications of this technique where we have used 1-D STICS to quantify flow in 10 μm wide by 20 μm tall channels in PEGDA hydrogels. Finally, we are using 2-D STICS, which has previously been demonstrated to map intracellular solute transport, to quantify 2D flow fields at the tissue scale. We have mapped the flow at the inlet and outlets of hydrogels channels and will extend the use of 2D-STICS to quantify solute convection in porous musculoskeletal tissues.

6 CALCIUM SIGNALING OF IN SITU CHONDROCYTES UNDER UNCONFINED COMPRESSION

Mengxi Lv, Yilu Zhou, Liyun Wang, X. Lucas Lu

Mechanical stimuli can regulate the phenotype and metabolism of chondrocytes in articular cartilage. As one of the earliest responses of chondrocytes to mechanical stimulation, intracellular calcium ($[\text{Ca}^{2+}]_i$) signaling is the upstream of numerous mechanotransduction pathways. Chondrocytes in monolayer have been proven to exhibit $[\text{Ca}^{2+}]_i$ response to various mechanical stimuli. However, little is known about the mechanically induced $[\text{Ca}^{2+}]_i$ oscillation of *in situ* chondrocytes, which is challenged by significant displacement of cells during loading. In this study, a newly designed microscope loading device allowed the instantaneous recording of $[\text{Ca}^{2+}]_i$ signaling of *in situ* chondrocytes during compressive loading applied on the cartilage explant. Furthermore, we investigated the roles of seven pathways in modulation of $[\text{Ca}^{2+}]_i$ response of chondrocytes. In results, Compressive loading applied on cartilage explants induced $[\text{Ca}^{2+}]_i$ signaling in $19.3 \pm 1.3\%$ of the cells, significantly higher than $8.3 \pm 0.94\%$ in non-loading control group ($p < 0.0001$), and the time for the first peak to relax to the 50% of its magnitude was significant shortened (22.1 ± 1.3 s vs. 29.2 ± 1.9 s, $p < 0.005$). Moreover, removal of extracellular Ca^{2+} almost abolished the $[\text{Ca}^{2+}]_i$ responses of *in situ* chondrocytes with merely 0.9% cells responded. Depletion of ER-operated calcium by blocking ER membrane Ca^{2+} pumps, P2 receptor and PLC-IP3 pathway led to the significant reduction in $[\text{Ca}^{2+}]_i$ signaling response rate. Inhibition of three ion channels, including mechanosensitive ion channels, T-type voltage gated calcium channel and transient receptor potential cation channel4 also significantly diminished the proportion of cells responding to mechanical loading. In conclusion, the effect of mechanical loading on chondrocyte is directly correlated with $[\text{Ca}^{2+}]_i$ response and seven pathways modulated the mechanically induced $[\text{Ca}^{2+}]_i$ signaling in an orchestrated manner.

7 A MULTI-SCALE APPROACH IN ANALYZING FLUID/SOLUTE FLOW IN MECHANICALLY LOADED BONE

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Transport of nutrients, signaling molecules, and fluid in the bone lacunar-canalicular system (LCS) is critical for osteocyte survival and function. The fluorescence recovery after photobleaching (FRAP) approach has been used to quantify load-induced fluid and solute transport in the LCS but the measurements were limited only to cortical regions 30–50 μm underneath periosteum due to technical difficulties. We aimed to expand our understanding of load-induced fluid and solute transport in both trabecular and cortical bone using the image-based finite element analysis (FEA) approach. A three-dimensional (3D) linear elastic FEA model of a whole murine tibia under axial loading was first constructed to calculate matrix deformations and a segment of the 3D model was then imported to the biphasic poroelastic analysis platform FEBio to predict the load-induced fluid pressure, and interstitial solute/fluid flow through LCS in both cortical and trabecular regions. The secondary flow effects such as the shear stress and/or drag force acting on the osteocytic cell membranes were derived using the ultrastructural models of Brinkman flow in canaliculi. The material properties assumed in the FE models were validated against the experimentally measured strain and the FRAP data. Our results demonstrated feasibility of this computational approach in estimating fluid flux in the LCS and the cellular stimulation forces (shear and drag forces) for osteocytes in both cortical and trabecular bones at arbitrary locations, allowing further studies of how osteocytes' activation correlates with functional bone formation *in vivo*. Using this new tool, fluid flow and cellular stimulations can be quantified in mechanically loaded bone, enhancing our understanding of bone adaptation processes.

8 QUANTIFYING DIFFUSION OF FLUORESCENT SOLUTES IN STRAINED POROUS, VISCOELASTIC MATERIALS USING CORRELATION SPECTROSCOPY

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BIOMEDICAL ENGINEERING PROGRAM

Osteoarthritis (OA) is a progressive degenerative disease, which results in altered solute-matrix interactions and load-induced fluid flow in affected articular cartilage. We propose that the direct quantification of changes in the microfluidic properties of cartilage *in situ* could be useful as a diagnostic measure of OA, especially earlier in disease progression. The present study validated the use of Fluorescence Correlation Spectroscopy (FCS) and Raster Image Correlation Spectroscopy (RICS) to quantify the equilibrium diffusivity of various solutes in agarose and cartilage. In this study we first demonstrated diffusion attenuation with increasing solute size and increasing gel concentration. Subsequently, we characterized *in situ* diffusive properties of solutes in three distinct zones of bovine articular cartilage (superficial, middle, & deep zones). Future work looks to extend the present work to the quantification of diffusion within osteoarthritic articular cartilage, as well as to the use of Spatiotemporal Image Correlation Spectroscopy (STICS) to permit quantification of load-induced solute convection *in situ*. We believe that these studies will improve our knowledge of solute-matrix interactions and fluid flow in articular cartilage, and enhance our understanding of cartilage mechanobiology and health.

9 BISPHOSPHONATE RESCUED ARTICULAR CARTILAGE FROM TRAUMA DAMAGE

Yilu Zhou, Miri Park, Enoch Cheung, Liyun Wang, X. Lucas Lu

We and others found that systemic injection of zoledronic acid (ZA), a bisphosphonate, could suppress the post-traumatic osteoarthritis (PTOA) in various animal models. Here, we hypothesized that 1) ZA can rescue the cartilage from traumatic damage under *in vitro* culture without the presence of bone, and 2) the chondro-protective effects of ZA is related to the inhibition of chondrocyte mevalonate pathway. Cartilage explants from calf knee joints were cultured in serum medium for one week to simulate joint bleeding induced trauma on cartilage, and then cultured in chondrogenic medium supplemented with or without ZA. The longitudinal mechanical properties, spontaneous intracellular calcium ($[Ca^{2+}]_i$) signaling of chondrocytes, GAG, collagen content, and gene expression were measured. To investigate the involvement of mevalonate pathway, mevalonate derivatives (farnesol (FOH), geranylgeraniol (GGOH)) were supplemented together with ZA to check whether they can offset the chondro-protective effects of ZA. After serum damage, mechanical moduli of explants treated with ZA are significantly higher than the control. Similar trend was found for the $[Ca^{2+}]_i$ responsive percentage of chondrocytes and GAG content. In ZA group, expression of anabolic genes (type I and II collagens) were significantly higher, while catabolic gene (ADAMTSS and MMP-13) were significantly lower. GGOH significantly dampened the chondro-protective effects of ZA in terms of mechanical properties. $[Ca^{2+}]_i$ responsive percentage in the ZA+FOH group was lower than the ZA+vehicle group. We found that ZA can rescue the trauma-damaged cartilage explants during *in vitro* culture without the presence of bone. This chondro-protective effect of ZA is related to the inhibition of mevalonate pathway, specifically the protein geranylgeranylation. Geranylgeranylation is required for MMP13 release. Therefore, local treatment of bisphosphonate could represent a new therapeutic technique to prevent the initiation of PTOA.

10 COMPARING MINERALIZATION LEVELS AMONG CK2 BLOCKING PEPTIDES

Prashanth Moku, Miho Maeda, Anja Nohe

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Osteoporosis is a condition in which bones become prone to fractures due to decreased bone density. Osteoclasts and osteoblasts are cells responsible for breaking down old bone cells and forming new bone cells, respectively. Casein Kinase 2 (CK2) is an enzyme known to mediate osteogenesis. Bone morphogenetic protein 2 (BMP2) is a growth factor that controls differentiation of stem cells into adipocytes, osteoblasts, and osteoclasts. The interaction of casein kinase II (CK2) and BMP receptor type Ia (BMPRIa) releases CK2 from the BMPRIa receptors inducing mineralization. CK2 blocking peptides named CK2.1, CK2.2, and CK2.3 were designed to induce cell response from the BMPRIa receptor. CK2.3 induces osteogenesis whereas CK2.2 induces adipogenesis.

The study was carried out in C2C12 cells. The cells were exposed to CK2.3 and CK2.2, providing different levels of osteogenesis. I used peptides CK 2.2 and 2.3 to measure levels of mineralization under varying concentrations of the peptides. C2C12 cells were grown and treated with different concentrations of CK2 peptides. Results showed that CK 2.3 promoted highest levels of mineralization. Lipid droplets were observed in CK2.2 at high levels. Further research on the effect of CK 2.3, in comparison to treatments with CK2.2 as well as BMP2, on levels of osteogenesis can provide insight into bone formation of varying cell types and stages.

11 PEPTIDE CK2.3 INDUCES MINERALIZATION IN PATIENT SAMPLES

Miho Maeda, Christopher Bowens, Jeremy Bonor, Anja Nohe

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Osteoporosis is a progressive bone disease that leads to weakened bones. One in two women over the age of 50 will have an osteoporosis related fracture in their lifetime. The mortality rate during the year following an osteoporosis related hip fracture is about 20% in women. Existing treatments for osteoporosis are limited in efficiency, and thus new treatments are desperately needed. Bone morphogenetic protein 2 (BMP2) is a promising therapeutic for osteoporosis, however, mesenchymal stem cells (MSCs) stimulated with BMP2 differentiate into bone as well as adipocytes. The BMP2 signaling pathway that leads to osteogenesis is through the BMPRI and BMPRII receptors. The release of casein kinase 2 (CK2) from BMPRIa was found to be a molecular switch that directed the differentiation of MSCs into osteoblasts. Three potential phosphorylation sites on BMPRIa by CK2 were identified, and novel mimetic peptides were made that blocked one of these three sites. Osteoblasts from patient femoral heads were isolated and treated with either BMP2 or CK2.3. We found that CK2.3 was able to significantly induce mineralization in patient samples.

12 BONE BIOREACTOR TO MAINTAIN BONE CELL VIABILITY *EX VIVO*

Aparna Swarup, Miho Maeda, Jeremy Bonor, Hemanth Akkiraju, Vrathasha Vrathasha, John Nguyen, Prashanth Moku, Anja Nohe

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Current research in drug discovery involves testing the effect of the drug on animals. Once successful the drug is moved to trials in primates until finally tested in clinical trials on humans. However, a majority of drugs fail in these trials, even though they showed promising results in initial studies. This may be due to differences between animal and human physiology. There is a need of better testing. Bioreactors allow for the maintenance of the human tissue in a similar environment as the human body. Therefore it is a powerful tool for drug testing.

Currently research is being conducted using bioreactors to culture and test the effect of drugs on cells and tissues like liver, lungs, heart and kidneys. However, very little research has been done on bone-based bioreactors. Bone tissue hosts multiple stem cell lineages, making it an important tissue for drug testing. There is a need to identify and test new therapeutics for bone diseases. Bone diseases worldwide affect 8.9 million people and account for 24 billion dollars spent in treating fractures due to osteoporosis.

This study aimed to design a bioreactor for maintaining veal bone in a constant environment keeping the tissue alive. The bioreactor was designed as a closed system with stable temperature supplied with 5% CO₂. A pump allowed media to flow continuously through the four main arteries of a femoral head. Using the bioreactor we show a 50% increase in cell survival as compared to control tissue. This bone bioreactor model will be used to test the effect of peptide CK2.3 that has shown potential for increased mineralization in bone.

POSTER PRESENTATIONS

Gait

13 PRELIMINARY STUDY OF PLANTAR FLEXOR MUSCLE MOMENTS DURING BODY WEIGHT SUPPORTED WALKING

Anahid Ebrahimi, Brian A. Knarr, Steven J. Stanhope, Jill S. Higginson

The objective of this study is to use musculoskeletal modeling to characterize the timing and magnitude of the individual plantar flexor muscle moments contributing to peak ankle plantar flexion moment (pAPM) across different levels of dynamic body weight support (BWS). A subject (50.98kg, 1.54m) walked on an instrumented split belt treadmill under three BWS conditions (0%, 20%, and 40% BWS) at her self-selected speed. Force data from the BWS system along with motion capture and force plate data from one gait cycle were input into a standard 23 degree of freedom, 92 muscle actuator OpenSim model for each condition. Results showed pAPM occurred slightly earlier in the gait cycle with increased BWS. Peak gastrocnemius plantar flexion moment always occurred before pAPM while peak soleus moment occurred after it. In general, peak muscle plantar flexion moment decreased when BWS was greater than 20%, as did muscle plantar flexion moment at the time of pAPM. While the pAPM decreases linearly with increased BWS, these data indicate no linear decrease in plantar flexor muscle moments with increased BWS. If these trends hold with more subjects, clinicians administering BWS gait retraining can interpret these results in two ways: (1) Providing 20% BWS may require the same use of the patient's ankle plantar flexor muscles as without BWS and (2) Providing 40% BWS may require much less use of these muscles compared to without BWS. Future studies will enlist more subjects and include an induced acceleration analysis, which can deduce the contribution made by the plantar flexor muscles to the acceleration of the center of mass.

14 A MODEL TO CUSTOMIZE AFO FOOTPLATES TO PRESERVE SHANK PROGRESSION WITH LIMITED ANKLE DORSIFLEXION

Bretta L. Fylstra, Travis R. Pollen, Elisa S. Arch

The main purpose of gait is to progress the body forward and the shank is critical for achieving this forward progression. Individuals with limited ankle dorsiflexion range of motion (ROM) will often have impaired shank progression and therefore difficulty with gait. Ankle-foot orthoses (AFOs) can be prescribed to achieve typical shank progression, however, these AFOs lock the ankle in a static position and do not allow any ankle movement. Alternatively, we hypothesize that by adding a rocker bottom to the footplate, the foot-to-floor angle can be utilized to substitute for the limited ankle angle. The purpose of this study was to develop a mathematical model to predict how to customize the footplate rocker to promote natural shank progression for individuals with different ankle ROM limitations. In the model developed, trajectories of the ankle joint center (AJC) and knee joint center (KJC) are calculated based on the subject's anthropometrics and landmarks on the AFO model. Different ankle ROM limitations can be input and the rocker start location and radius of curvature can be customized to best mimic typical AJC and KJC trajectories. The calculated AJC and KJC were graphed versus data collected from the lab's database for three different ankle ROM limitation conditions. Comparing the graphs, the simulated points match closely with the actual data. An AFO with removable footplate and ankle ROM lock was developed so the model can be tested. Future studies will experimentally evaluate this model's predictions using the designed AFO. These studies will aim to experimentally prove the model and see how replacing ankle ROM with foot-to-floor motion affects overall gait kinematics. This study successfully developed a model for personalized AFO footplates and will be implemented into AFOs for testing and future experiments.

15 THE QUANTIFIED SELF: DEVELOPMENT OF WEARABLE TECHNOLOGY

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The Quantified Self is today's movement to incorporate new innovations and technological advancements into a person's daily life to measure psychological state and physical performance. Some research has shown that people are becoming more inclined to use wearable technologies to improve health and habits. The details of flow and storage of data from these devices is expected to become increasingly more important as the wearable devices continue to collect data at higher temporal resolution.

The PDShoe, a vibratory feedback insole, was developed to gather and transmit data between an instrumented insole and a computer. While user's gait data is both transmitted wirelessly and stored to internal memory, the PDShoe software has been revised to improve file organization and prevent data loss. Through a series of both hardware and software changes, device functionality has been expanded to improve data flow and management. This paradigm of data and device command exchange is one that can be applied to other controllable data collection systems.

16 THE ROLE OF CORTICAL INHIBITION IN WALKING FUNCTION AND RESPONSES TO REHABILITATION IN INDIVIDUALS POST-STROKE

Chloe Gordon, Jacqueline Palmer, Stuart Binder-Macleod

Introduction: Despite the importance of walking function recovery following stroke, the neurophysiologic mechanisms that drive lower extremity motor recovery are poorly understood. Upper extremity research has shown that a balance of cortical facilitation and inhibition is important for good functional motor recovery and that improvements in balance through rehabilitation improves motor performance. In the lower extremity, cortical facilitation has been shown to be related to functional walking recovery, but the role of cortical inhibition is unknown. The purpose of this study is to evaluate the relationship between cortical inhibition and lower extremity function and response to rehabilitation.

Methods: Ten individuals with chronic stroke completed this study. Transcranial Magnetic Stimulation was used to elicit motor evoked potentials (MEPs) from the paretic and nonparetic tibialis anterior muscles while participants maintained a light dorsiflexion contraction. Comfortable and fastest walking speeds were calculated from a 10-meter walk test. A subset of five participants completed a session of gait training with functional electrical stimulation (FES) to the dorsi- and plantarflexors. Cortical silent period (SP) was calculated as the period from the stimulus artifact to the resumption of background EMG activity levels.

Results: Preliminary results show a positive correlation between paretic SP and gait speed modulation ($r=0.7388$, $p<0.05$). In response to a session of rehabilitation, there were no changes in SP duration (pre= 0.215 ± 0.073 , post= 0.200 ± 0.033 , $p=0.484$).

Conclusions: Results of this study indicate that cortical inhibition is positively related to lower extremity function post-stroke, suggesting that the role of cortical inhibition in motor recovery differs between upper and lower extremities. Cortical inhibition was unchanged following a session of rehabilitation, indicating that improvements in biomechanical function and enhancement of corticomotor input primarily occur through cortical facilitation.

17 EFFECT OF UNILATERAL AND BILATERAL LOAD CARRIAGE ON GAIT AND TRUNK ORIENTATION IN HEALTHY YOUNG ADULT FEMALES

Kevin M. McGinnis, Laura Van Der Post, Jill S. Higginson

Introduction: The majority of the population carries some type of bag to transport their personal items, such as a backpack, one-shoulder tote bag, or briefcase. Carrying a backpack daily has been found to cause back pain in adolescents and pain was correlated with carrying time. The objective of this study was to determine the alterations in spatio-temporal parameters and trunk orientation due to unilateral and bilateral load carriage.

Methods: Nine healthy female college students were recruited for this study. Subjects walked at a self-selected pace and 4–5 gait cycles were analyzed. Four scenarios were tested: normal walking, 20% body weight added to the left and right shoulder, and 20% body weight in a two shoulder backpack.

Results: Subjects walked significantly slower in the bilateral condition compared to all other conditions. Subjects carrying the bilateral load had a significantly reduced stride length compared to the control. Double support percentage increased for all conditions compared to control. Significant differences existed between left and right step length at all conditions (L>R) except for right unilateral load carriage. There were significant decreases in average step length between control and left unilateral, right unilateral, and backpack conditions.

Discussion: There were multiple spatio-temporal alterations made due to adding 20% body weight both unilaterally and bilaterally. Subjects walked slower and had increased double support percentage. Subjects were taking slower and smaller steps and increasing support in order to deal with the extra weight. These changes highlight an important issue that could affect anyone who carries extra weight as part of their daily routine.

18 A KINEMATIC AND ENERGETICS MODEL OF SHANK PROGRESSION DURING STANCE

Travis Pollen, Elisa S. Arch, Steven J. Stanhope

Transfemoral amputees depend on prosthetic ankle-feet to ambulate. However, due to the design of modern energy-storing-and-returning prosthetic devices, analyzing prosthetic systems using traditional methods proves challenging. As a result, objective guidelines for the prescription and customization of these systems are lacking. Component selection on the part of the prosthetist is left up to subjective measures such as training and intuition. Roll-over shape, the geometry the ankle-foot deforms to during stance, has been proposed as an improved characterization method. While useful, roll-over shape fails to account for the period of late stance, during which important propulsive functions occur. The kinematics (translations and rotations) and energetics (flow of segmental power) of shank progression may provide a more complete description of ankle-foot function. The purpose of this study was to quantify the kinematics and energetics of shank progression over the entire stance phase of typical gait. Overground instrumented gait analysis was conducted for ten typical adult participants walking at normal velocity. From the interrelationships between the ankle, foot-to-floor, and shank angles, as well as the dynamics of energy flow into the shank, kinematic and energetics models of shank progression were developed. In the future, these models can be used to design novel prosthetic ankle-foot systems that mimic natural shank progression, which may lead to improved functional outcomes for individuals with transfemoral amputation.

19 CHARACTERIZING TREADMILL PERFORMANCE TO SUPPORT AN ENHANCED ERGOMETRY PROTOCOL

Alex Razzook, Dustyn Roberts, Bill Rose, Dave Edwards, Steven Stanhope

Variable speed/incline treadmills are ubiquitous in both medical and rehabilitation research settings. When combined with indirect calorimetry, researchers manipulate belt speed and incline angle to biomechanically probe a subject's physiological performance. Yet, little is known how treadmill reported measures of speed and incline may vary across subjects. Thus, the purpose of this study was to characterize treadmill performance to support a future ergometric protocol where inter-subject work-load rates must be rigorously controlled.

A lifespan fitness 5000i commercial treadmill was used for all tests. Belt speed was measured using a SHIMPO digital contact tachometer (DT-107A). Treadmill incline angle was measured using a triaxial accelerometer. Power consumption was measured using a hall effect sensor repurposed from a commercially available power sensor (P3 International). All tests were repeated three times. A cylindrical, metallic 91.3N calibration weight served as the load.

Unloaded, the treadmill consistently over-estimated both belt speed 0.03 ($\pm 0.01SD$) mph and inclination angle 0.2 ($\pm 0.2SD$) Deg across the range of speeds (0 to 5.0 mph) and angles (0 to 8.6 Deg) tested. In the loaded tests, belt speed was reduced by 0.09 ($\pm 0.11SD$) mph with minimal change in inclination angle 0.2 ($\pm 0.3SD$) Deg. The treadmill consumed 9.3 ($\pm 0.2SD$) watts at 0.0 mph up to 256 ($\pm 1.2SD$) watts at 5.0 mph. Belt speed measures appear sensitive to applied loads indicative of a feed forward treadmill control design. When coupled with the repeatability of the power consumption measures, experimentally calculated correction factors may be used to precisely prescribe inter-subject work-load rates for enhanced ergometry.

20 HUMAN-EXOSKELETON HYBRID MODEL TO PRODUCE STABLE GAIT THROUGH INTER-LIMB COORDINATION

Duanyi Wei, Ioannis Poulakakis, Jill S. Higginson

DEPARTMENT OF MECHANICAL ENGINEERING

Robotic gait training has shown mixed success in improving functional ambulation in post-stroke individuals. As human locomotion is composed by movements of both sides, it clearly involves well-organized inter-limb coordination, which is neglected in current gait-training robots. The objective of this study is to construct a low-dimensional model to represent the asymmetric, hybrid human-exoskeleton locomotion. We then use this model to test that a control framework for the robotic limb that accounts for the contralateral human limb dynamics can achieve stable gait. The sagittal-plane biped model has a prismatic leg representing the "human limb" on one side, a two-link structure representing the exoskeleton on the other, and a point torso mass at the hip. The human side is actuated by the hip and robotic actuators are located at contralateral hip and knee joints. The dynamics of the model are obtained using Lagrangian methods. Coordinated locomotion is achieved by enforcing output functions that prescribe the motion of the robot relative to the human to zero. Input-output linearization is adopted to compute the torque necessary to maintain the output at zero. The stability of the gait (able to recover nominal walking pattern under perturbations) can be studied using analytical Poincaré mapping, and it is guaranteed if the eigenvalues of the linearized Poincaré map have magnitudes less than 1. Despite apparent asymmetry in the limbs, the results have shown success of inter-limb coordination strategy in stabilizing the gait cycle in the presence of disturbances. In addition, the model demonstrates close resemblance to human gait kinematics and GRF profile.

POSTER PRESENTATIONS

Orthopaedics

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HEAD IMPACT EXPOSURE IN COLLEGIATE WOMEN'S SOCCER

Jaclyn B. Caccese, L. C. Lamond, Thomas W. Kaminski

BIOMECHANICS AND MOVEMENT SCIENCE PROGRAM

The negative long-term effects of repeated subconcussion from heading a soccer ball have been reported in post-collegiate players; however, these same deficits are not apparent in youth and collegiate athletes over an acute bout of heading or even over the course of a season. The first step in determining the onset of these long-term effects is to quantify head impact exposure over the course of a season. Thus, the purpose of this study was to quantify head impact exposure in collegiate women's soccer players over one season of play. Twenty-four women's collegiate soccer student-athletes (age=19.7±1.2years; height=168.3±4.2cm; mass=62±4.5kg) participated in this study. Participants wore triaxial accelerometer, Smart Impact Monitors (SIMs) (Triax Technologies, Norwalk, CT), in headbands throughout all practices and games. The SIMs were positioned at the back of the athlete's head to avoid ball contact. A 20g threshold was set on the accelerometers, so that accelerations from simply running and jumping were not recorded. Over one season, 1,207 impacts were visually observed across 24 participants. Of the 667 impacts that exceeded the 20g threshold, 236 occurred during practices and 431 during games. The average linear ($p=0.001$) and angular ($p=0.007$) accelerations for head impacts above the 20g threshold were significantly higher in games (linear acceleration=46.8±15.0g; angular acceleration = 6.8±3.1krad/s²) than in practices (linear acceleration=40.8±14.0g; angular acceleration=5.1±2.6krad/s²). This statistically significant difference may not be clinically significant, considering concussions are likely to occur between 80–100g. This suggest that heading during practice may be just as hard as heading during game play.

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THE RELATIONSHIP BETWEEN A MEASURE OF DYNAMIC BALANCE AND A MOVEMENT ASSESSMENT

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The Star Excursion Balance Test (SEBT) is a valid and reliable dynamic balance test used to identify functional deficits associated with lower extremity injury. Movement assessments are also used clinically to identify injury risk factors. Predictive factors for decreased SEBT performance are unknown and identification of such factors would be clinically useful for injury prevention. It is hypothesized that postural deviations observed during a movement assessment, particularly in the proximal kinetic chain (PKC), would be contributing factors to dynamic balance deficits.

Purpose: To determine the relationship between dynamic balance and a movement assessment in an effort to identify causes of decreased SEBT performance.

Methods: Forty-seven track athletes (male=25, female=22; age, 20.8±1.2 years; mass, 71.3±15.7 kg; height, 176.3±9.3 cm) completed the SEBT (anteromedial, medial, posterior reach directions) and a movement assessment (single-leg and an overhead squat). Correlation (r_{pb}) coefficients were calculated to determine the relationship between normalized SEBT reach distances and movement assessment scores indicating the presence/absence of postural deviations at four kinetic chain checkpoints (foot/ankle, knee, lumbo-pelvic-hip complex, shoulder/c-spine). Inter-tester reliability of the movement assessment was also calculated using percent agreement.

Results: A negative relationship (medium effect size) was found between SEBT posterior reach and forward lean during the overhead squat ($r=-.23$, $p=.03$). Anteromedial SEBT reach was negatively correlated with rounding of the low back during the overhead squat ($r=-.24$, $p=.02$). Using squats to assess movement demonstrated fair to good percent agreement amongst raters ($r=.76-.99$).

Conclusion: Postural deviations in the PKC during an overhead squat are associated with decreased SEBT performance. This provides evidence for PKC involvement in decreased dynamic balance scores and lower extremity injury risk, and supports the incorporation of the PKC into injury assessment and prevention efforts.

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MECHANICS OF LOADED VERTICAL JUMPING: F-V AND P-V RELATIONSHIPS

Daniel Feeney, Thomas Kaminski, Steven J. Stanhope, Anthony Machi, Slobodan Jaric

BIOMECHANICS AND MOVEMENT SCIENCE PROGRAM

The aims of the present study were to (1) explore the pattern of force-velocity ($F-V$) relationship of leg muscles in a multijoint movement, (2) evaluate the reliability and concurrent validity of the obtained parameters of the $F-V$ relationship, and (3) explore the load associated changes in the muscle work and power output. Subjects performed maximum vertical countermovement jumps with a vest ranging 0–52% of their body mass. The ground reaction force and leg joints kinematics and kinetics were recorded. The data revealed a strong and approximately linear $F-V$ relationship (individual correlation coefficients ranged from 0.78–0.93). The relationship slopes, F - and V -intercepts, and the calculated power were moderately-to-highly reliable ($0.67 < ICC < 0.91$), while their concurrent validity with respect to the directly measured values was on average moderate. Despite a load associated decrease in both the countermovement depth and absolute power, the absolute work done by the center of mass increased, as well as the relative contribution of the knee work and power as compared with the hip and ankle. Therefore, the loaded vertical jumps could be developed into a routine method for testing the mechanical properties of leg muscles, while the load associated changes in both the absolute and individual joints' work and power could reveal the mechanisms of adaptation of multi-joint movements to different loading conditions.

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METHODS FOR ESTIMATING SCAPULAR KINEMATICS DURING UPPER EXTREMITY CYCLING

Elizabeth A. Rapp, Kristen F. Nicholson, R. Tyler Richardson, Therese E. Johnston, James G. Richards

Upper extremity (UE) ergometry is a therapy for patients with spinal cord injuries (SCI), however, its effect on the shoulder complex is unknown. Motion capture using surface markers fails to measure dynamic scapular orientations due to scapular motion beneath the skin. Other methods of measuring scapular kinematics have additional limitations. We aimed to compare the accuracy of the acromion marker cluster (AMC) method and the generalized linear regression (GLR) method for estimating scapulothoracic (ST) orientation during UE cycling. We hypothesized that the GLR would provide greater accuracy than the AMC under static conditions, and differences between the two methods during dynamic testing would be greater for SCI subjects. One healthy subject and one with a recent SCI were analyzed. Markers were placed on bony landmarks and scapular markers were re-palpated in eight different positions. Ten seconds of kinematics were collected during cycling. The relationship between humeral orientation, acromion process displacement and scapular orientation was assessed for four positions to generate predictive equations. Scapular orientations from the AMC and GLM estimations were compared to the corresponding palpated positions. For the motion trial, the differences in the GLM and AMC estimated ST orientations were calculated across the cycle. For static results, the GLR returned smaller errors than the AMC. The reduction in error was more pronounced in the SCI subject. During motion, there were notable differences between the two methods' estimates of ST angles, and the differences were generally larger for the SCI subject. This suggests the difficulty of finding a measurement technique that captures pathological scapular kinematics. As the static results showed that the GLR was more accurate, we look to further explore under dynamic conditions.

25 EVALUATION OF GLENOHUMERAL MUSCLE MOMENT ARMS OF A NEW MUSCULOSKELETAL MODEL OF THE SHOULDER

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Musculoskeletal modeling is capable of estimating muscle forces that cannot be directly measured; however, the validity of the results must first be assessed to ensure that the model recreates in vivo mechanics. Moment arms define the function of a muscle about a joint and dictate the mechanical advantage with which it operates. Evaluation of moment arms represents an important step in model verification as they strongly influence simulation predictions. A new shoulder model (UDSM) which permits unprescribed, physiological motion of the scapula has been developed for assessment. This study compared the UDSM glenohumeral (GH) abduction moment arms with published cadaveric data. Continuous GH abduction moment arms for the deltoid, latissimus dorsi, pectoralis major, teres major, and rotator cuff muscles were calculated for the model. The model moment arms were assessed from (a) 2.5° to 120° shoulder abduction with a prescribed scapular rhythm which matched the kinematics of the experimental setup in the cadaveric study and (b) using unprescribed scapular motion during in vivo shoulder abduction obtained with motion capture. The model GH moment arms were qualitatively compared with published cadaveric data. The UDSM moment arms accurately reflected the functional role of each muscle and their magnitudes compared favorably with cadaveric data. The moment arms of the UDSM driven by in vivo motion were comparable to those of both the first model condition and cadaveric data with only a few muscles displaying appreciable differences. This initial analysis establishes that the UDSM GH abduction moment arms are similar to cadaveric data while allowing for unprescribed scapular motion.

26 DESIGN AND TESTING OF A NOVEL DEVICE TO QUANTIFY CALF MUSCLE STRENGTH

Kimberly L. Rowe, Elisa S. Arch

Rehabilitation approaches for patients post-stroke are moving toward personalized prescriptions. Accurate measurement of calf muscle strength is a crucial factor in effectively prescribing personalized ankle-foot orthoses; however calf muscle strength is currently measured on a qualitative scale. Therefore, the ability to quantitatively measure calf-muscle strength in a clinical setting is crucial. The purpose of this study was to develop and evaluate accuracy of a portable device to quantitatively measure calf muscle strength.

The underlying concept harnessed by the device is that calf muscle strength is expressed during gait as the peak plantar flexion moment. The current generation of the device consists of a foot plate and an adjustable rocker which changes the resultant moment arm. This current generation was improved over the initial prototype by increasing the strength, length, and width of the foot plate, as well as adding a small tooth at the front of the device to act as a stabilizer during use and a strap to secure the subject's foot on the footplate. The subject is instructed to tip the footplate while standing on one foot, and the rocker is adjusted until the subject can just tip the footplate about the rocker. Peak ankle moment is calculated by multiplying the length of the moment arm by the subject's body weight and provides a measurement of the strength of the calf muscle. Preliminary testing was carried out using the device on a forceplate with motion analysis targets. Device- and motion analysis-calculated moments were compared to assess the accuracy of the device. Future testing will be done to relate the peak ankle moment calculated during use of the device and the measurement of peak ankle moment during walking for both typical individuals and individuals post-stroke.

27 VISCOELASTIC PROPERTIES OF HEALING ACHILLES TENDON: A CASE SERIES

Jennifer A. Zellers, D. Cortes, Karin Gravare Silbernagel

Achilles tendon dysfunction is an injury that causes pain, impairments in strength and function as well as difficulty with physical activity. Currently, treatments are evaluated using clinical, functional and patient-reported outcomes. However, a limitation of these outcomes is the lack of evaluation of tendon structure and mechanical properties. A novel, non-invasive ultrasound elastography technique using continuous shear wave elastography (cSWE) has been developed to measure viscoelastic properties of the tendon. This technique has been validated and applied to a healthy population. The objective of this pilot study is to evaluate the viscoelastic properties with this new technique to explore if cSWE can be used as a biomarker for tendon health in three patients with Achilles tendon injury. Case one is a patient with interstitial tearing of the Achilles tendon (shear modulus = 73.55 kPa on symptomatic side, 141.42 kPa on asymptomatic side; viscous modulus = 16.6 Pa-s on symptomatic side, 51.3 Pa-s on asymptomatic side). Case two is a patient with Achilles tendinopathy (shear modulus = 88.68 kPa on symptomatic side, 122.62 kPa on asymptomatic side; viscous modulus = 25.2 Pa-s on symptomatic side, 48.8 Pa-s on asymptomatic side). Case three is a patient seven weeks post-Achilles tendon rupture with conservative management (shear modulus = 101.22 kPa on symptomatic side, 92.69 kPa on asymptomatic side; viscous modulus = 28.3 Pa-s on symptomatic side, 68.4 Pa-s on asymptomatic side). This pilot data indicates that this technique can identify differences in tendon viscoelastic properties in a variety of different tendon pathologies, however, additional studies with larger numbers of subjects are required.

POSTER PRESENTATIONS

Osteoarthritis

28 ALTERED MEDIAL TO LATERAL
TIBIOFEMORAL LOADING
ENVIRONMENT MAY BE PRESENT IN
OSTEOARTHRITIS

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Mechanical loading of the joint is frequently implicated in the development and progression of knee osteoarthritis. Axial loading alone likely does not completely characterize the loading environment as the area of load distribution significantly influences load transmission across the joint. The aim of this study is to investigate whether the ratio of loads between the medial and lateral tibiofemoral joints reflects the ratio of loading area in persons with knee osteoarthritis and age matched control subjects. It is hypothesized that control subjects will demonstrate preservation of the loading environment irrespective of the magnitude of joint loading while OA subjects will not. Medial to lateral load distributions were determined from 1st and 2nd peak knee adduction moments and the knee adduction impulse while medial to lateral cartilage contact ratios were determined from weight bearing MRIs. Data were analyzed using linear regression analysis with alpha = 0.05. Preliminary results from 11 control subjects and 7 OA subjects confirm our hypothesis. As control subjects increase the relative loading of their medial tibiofemoral compartments, there was a corresponding increase in medial to lateral contact area for all knee adduction terms ($p = 0.00 - 0.04$), while the OA subjects demonstrated no relationship ($p = 0.54 - 0.72$) between the variables. These preliminary results suggest that in addition to the elevated joint loads seen in the OA subjects, a maladaptive loading environment may also be present.

29 KINEMATIC/KINETIC DIFFERENCES
BETWEEN SUBJECTS WITH/
WITHOUT KNEE OSTEOARTHRITIS
(OA) AFTER UNILATERAL ANTERIOR
CRUCIATE LIGAMENT RECONSTRUCTION
(ACLR)

Ashutosh Khandha, Kurt Manal, Lynn Snyder-Mackler and Thomas S. Buchanan

Introduction: Kinematic/kinetic differences in the involved knee between subjects with/without knee OA five years after unilateral ACLR were evaluated at the first peak of vertical ground reaction force (vGRF) during gait. We further evaluated the effect of typical kinematics/kinetics on medial tibial cartilage stress distribution, for a non-OA vs. OA subject.

Methods: Thirty-seven unilateral ACLR subjects (14 females, 23 males, Age Range: 14 to 46 years) at the five-year post-surgery time point were included. Eight out of 37 subjects showed signs of OA in the medial compartment. The testing protocol included gait and electromyography (EMG) analysis. A validated Hill-type EMG-informed musculoskeletal model was used to estimate joint force. Finite element analysis was further used to compare the cartilage stress distribution for a typical representative non-OA vs. OA subject, at the first peak of vGRF.

Results: The OA group demonstrated significantly lower flexion angle (non-OA: 25.1 ± 4.3 , OA: 17.7 ± 2.2 , $p = 0.01$, unit: Degrees) sagittal plane moment (non-OA: 4.9 ± 1.0 , OA: 3.4 ± 1.1 , $p = 0.01$, unit: % Body Weight * Height) and transverse plane moment (non-OA: 1.4 ± 0.3 , OA: 1.0 ± 0.2 , $p = 0.01$, unit: % Body Weight * Height). The OA group also demonstrated a lower joint force and a higher frontal plane moment, but these differences were not significant. Finite element results indicated that maximum stress near the medial margin of the medial tibial cartilage was higher for the OA subject. This is the region where radiographic osteophytes are commonly observed. These results can help solidify the link between altered joint mechanics and premature knee OA in unilateral ACLR subjects.



12th Annual Biomechanics Research Symposium Schedule of the Day

TIME	WHAT	WHERE
8:30	BREAKFAST & POSTER SET-UP	STAR CAMPUS – GLASS ATRIUM
9:00	WELCOME & INTRODUCTORY REMARKS	STAR CAMPUS – GLASS ATRIUM
9:15	PODIUM SESSION 1	STAR CAMPUS – GLASS ATRIUM
10:30	BREAK	
10:45	POSTER SESSION 1 (ODD #S)	STAR CAMPUS – MAIN CONCOURSE
11:45	LUNCH	STAR CAMPUS – ATRIUM CONFERENCE ROOMS: 111 & 113
12:45	KEYNOTE: DR. DAWN ELLIOTT	STAR CAMPUS – GLASS ATRIUM
1:45	POSTER SESSION 2 (EVEN #S)	STAR CAMPUS – MAIN CONCOURSE
2:45	PODIUM SESSION 2	STAR CAMPUS – GLASS ATRIUM
4:00	AWARDS SESSION	STAR CAMPUS – GLASS ATRIUM