Biomechanics and Dynamics of Sports

Alison Sheets - Nike, Inc.
Research goals

• Improve athlete performance
• Reduce injury risk
• Though:
  • Technique understanding
  • Equipment innovation
  • Training methodology
Presentation overview

- Two approaches for investigating athlete performance
  - **Simulation**
    - Gymnastics swing kinematic analysis
  - Experimentation
    - Balance as a predictor of injury and performance
- Future opportunities
Presentation overview

• Two approaches for investigating athlete performance
• Simulation
  • Gymnastics swing kinematic analysis
• **Experimentation**
  • Balance as a predictor of injury and performance
• Future opportunities
Swing and dismount to be simulated
Questions investigated?

• What joint movements and bar release parameters maximize dismount rotation?
• What physiological or geometric constraints limit performance?
• What can the gymnast do in flight and land balanced?
• Mathematically, what is a balanced landing?
Motivation to use simulation

• Gymnastics requires precisely timed movements
• New movements are encouraged

• Computer modeling, simulation, and optimization can:
  • Identify characteristics
  • Develop new maneuvers
  • Design equipment

Image from: http://www.fanpop.com/spots/shawn-johnson/
Range of simulation approaches

Muscle driven models

Simple models

Image from: http://opensim.stanford.edu/work/performance.html

Image from: http://movement.osu.edu/research.html
Simulation methods

• Measured external bar forces
• Specified gymnast model and segment inertias
• Quantified musculo-skeletal capabilities
• Derived and integrated equations of motion
• Optimized control torques to maximize performance
Gymnast and uneven bar model

- Bar model
  - Bar stiffness= 15 kN/m
  - Coefficient of friction $\mu= 0.85$

- Gymnast model
  - 4 segments
  - Inertias estimated using Yeadon’s method
  - Compliant shoulder
  - Torques at joints
  - 7 DoF
Model strength capabilities

- Joint torque generators:
  - Shoulder
  - Hip

- Torques created by muscles, function of:
  - Joint angle
  - Angular velocity
  - Muscle activation

- Properties determined experimentally
Joint torque activation optimization

- Motion described by nonlinear differential equations: \( \ddot{x} = f[\dot{x}(t), \overline{u}(t)] \)
  - Where: \( \overline{u}(t) = [A_s(t), A_{h1}(t), A_{h2}(t), t_f] \)

- Optimization finds \( \overline{u}(t) \) to maximize objective function: \( J = J_p - J_c \)
  - Evaluates overall performance
  - Measures performance quality
  - Constrains optimal solution
Can the gymnast model and control scheme calculate a realistic performance?
Swing matching results

- Red lines: simulated
- Dashed lines: experimental
- Circles: undeflected shoulder positions (top of arm)
- Crosses: hip joint centers

Vertical position (m)
Questions investigated?

• What joint movements and bar release parameters maximize dismount rotation?

• What physiological or geometric constraints limit performance?
Swing optimization

• Maximize rotations in flight
  \[ J_o = \frac{\omega(t_f) \Delta t_l + \gamma(t_f)}{2\pi} \]

• Constraints included as penalty functions
  \[ J = J_o - \sum c_i p_i^2 \]

• Optimization constraints
  • Rate of change of activation
  • Joint range of motion
  • Gymnast must not hit the low bar
  • Gymnast cannot exceed max grip strength
Optimal swing performance
Performance sensitivity to grip strength constraint

The graph shows the relationship between the maximum number of dismount revolutions and the maximum bar force (BW) for different grip strengths. The data points indicate a decrease in the maximum number of revolutions as the maximum bar force increases. The text box notes that the measured maximum bar forces during swings on women’s uneven parallel bars and men’s high bar with no low bar constraint.
Grip strength constraint limits system mechanical energy
Grip strength constraint limits system mechanical energy

- Max energy stored in bar then returned
Swing simulation conclusions

• Better understanding of gymnastics maneuvers

• **Grip strength** limits all performances
  • Less energy gained from muscular work
  • Less energy stored in bar
Strengths of Approach

- Calculate sensitivity of performance to:
  - Anatomical and physiological attributes
  - Technique
  - Equipment

- Identify parameters that are most important for performance

- Can explore “What-if’s?”
Challenges of approach

• Steps are not easily generalizable:
  • Subject-specific models
  • Movement specific simulation
  • Movement specific control

• Models and simulations must be validated

• Sport insights needed for optimization goals

• Optimization calculations are slow
Simulation improved understanding of gymnastics performance

Sometimes, no substitute for measuring how a subject moves
Experimental approach

• Measure athlete movements and forces
• Very accurate lab-based tools
• Experiments aim to elicit realistic performances
• Identify movement strategies for success
Motivation

- Balance deficits related to lower limb injuries and injury risk in “active” populations
  - Functional ankle instability\(^1\)
  - Ankle sprain\(^2\)
  - ACL injury\(^3\)

- Common injuries for elite and professional athletes

Are there sport specific characteristics of balance?

Are balance deficits and injury related in elite athletes?
Methods

• Collaboration with MJPC
• Tested static balance:
  • 20s, one bare foot, eyes closed
  • 34 elite football players
  • 14 elite soccer players
• Measurements:
  • Ground reaction forces
  • Point of force application
  • Gross movement quality
Parameters

- Center of pressure
  - Length of path
  - Average velocity
  - Standard deviation from average position
  - Area of ellipse enclosing 95% of data

- Athlete data
  - Sport
  - Injury history
  - Taping or orthotics
Strengths of approach

- Fast to measure
- Inexpensive, portable equipment
- Not strenuous for the athlete
- Immediate feedback
- Potential for quantitative evaluation of training effectiveness
Challenges of approach

• Limited information about athlete performance during trial
• Experiment performed in addition to training
• Indirect measurement for performance evaluation

Image from: http://mudfooted.com/why-flamingos-stand-on-one-leg/
Conclusions and Significance

• Biomechanics and dynamics can be used to understand sports performance

• Different approaches for different questions:
  • Simulations- “What can be?”
  • Measurements- “What is?”

• Need both approaches to move from descriptive to prescriptive understanding
Opportunities

• New tools needed for measurements in:
  • Game-like situations
  • Challenging environments
  • Interactions of multiple athletes

• Real-time feedback during training

• Multi-disciplinary teams to consider biological and mechanical factors
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