Objectives

• Review fundamental concepts on ski movement on a slope
• Provide technical solutions for generating and controlling forces to 'turn' skis
• Review the concept of inverse dynamics modeling
• Apply inverse dynamics to skiing
• Determination of muscle forces using models
Contents

1. Fundamental biomechanics of parallel skiing
2. Body actions to initiate ski movement
3. Inverse dynamics principles
4. Muscle forces by optimization
5. Ankle joint loading and shoes
6. Knee joint loading in skiing

I. Fundamental biomechanics of parallel skiing

• The logics of the procedure
  http://www.youtube.com/watch?v=LtMHcLgUFo4&NR=1
• The specific motion of the skis
• Which are the principles the skis have to follow?
• The four principal activities
• A necessary requirement: Balance
• Provisional result: Few simple technical elements
• Important consequences
Skiers perform the ski-motion by means of specific actions.

This implies the question: How do the skis move on the slope?

Then one has to ask: By which principles is this motion created?

Then one can explore: Which activities produce the required effects?

At the onset of edge-release the skis drift inward over the outside edges (faster at the tips): Inward-Drifting.

Following the edge change the skis drift outward over the inside edges (faster at the tails): Outward-Drifting.
**Investigation**

- 13 skiers
- Carrying out standard ski school demonstration techniques
- High/low offloading, etc.

**Results**

⟷ Ski movement 'low'

Arrows are velocities

Main result:
Any offloading happens before the turning of the skis set in
Which effect are needed for this to happen?

- lateral motion inward only needs lateral forces inward.
- lateral motion outward only needs lateral forces outward.
- The faster inward-drifting of the tips and faster outward-drifting of the tails need particular lateral forces.

The four principal activities

*The first principal activity: Falling-inwards (I)*

- By means of falling-inwards the skis become able to slip sideways.
  We need to distinguish two questions:
  - What is the effect of the lateral support of the body on the skis?
  - What is the effect of falling-inwards itself on the skis?
The four principal activities
The first principal activity: Falling-inwards (II)

• Only the lateral support of the skier \( F_{St} \) produces a lateral force inward \( F_s \) for the lateral motion, when drifting inward (a).

• Only the lateral support of the skier \( F_{St} \) produces a lateral force outward \( F_s \) for the lateral motion, when drifting outward (b).

The four principal activities
The first principal activity: Falling-inward (III)

• Falling inwards itself induces a reaction force \( F_s \) beyond/behind the centre/midpoint of the skis - because the bindings are located behind the center.

• When drifting inward (a) \( F_s \) brakes the slipping of the tails and therefore the tips are slipping faster.

• When drifting outward (b) \( F_s \) enhances drifting outward of the tails.
The four principal activities

The first principal activity: Falling-inward (IV)

Conclusion:

• Drifting inwards and drifting outward - and thus parallel-turns - can be effected in principle only by means of falling-inward.

• All essential conditions are fulfilled to perform the ski motion:
  Edge-change, inclination, ability to slip laterally and lateral forces.

The four principal activities

The second principal activity: Ski-change (I)

• Ski-change only means lifting the inside ski - without shifting the body weight to the outside ski.

• This activity is different from the so-called stepping.

• Effect is: immediate inward falling.
Conclusion:

- Because the ski change immediately causes falling inward, all essential conditions are fulfilled to perform the ski motion.
- Parallel turns can be effected in principle only by means of ski change.

The four principal activities

The second principal activity: Ski-change (II)

The third principal activity: Angulation-change (I)

- Angulation-change means the lateral motion changing from one angulation to the other.
- What is the effect of this activity?
- The lateral turning of the upper part of the body occurs in coincidence with a counter movement of the legs.
Conclusion:

- Angulation change obviously affects edge-change, ability to slip, inclination and lateral forces in a similar way as falling-inward.
- Thus parallel-turns can be effected in principle only by means of angulation-change.

The four principal activities
The third principal activity: Angulation-change (II)

Graphical Explanation:

- After initiation of the ski-turn the centre of gravity (KSP) has the tendency to maintain the direction of the motion (v).
- Because the centre of gravity is behind the centre of the skis (M_s), the drifting of the tails is enhanced (M).
When the skis perform a turn the skier will adopt a dynamic balance; i.e. despite inclination the skier does not fall.

In order to deviate from a linear direction of motion we need a lateral force $F_Z$ (centripetal force).

This force simply results from lateral support $-F_{St}$ and weight $F_G$.

The skier does not fall, because he continuously needs $F_Z$.

The centripetal force $F_Z$ has to vary continuously because $F_Z$ depends on the current radius of turn and the current velocity.

The only thing the skier has to do and can do for balance control is to vary the lateral support $-F_{St}$. 
4 simple key elements (actions) for parallel skiing

By means of falling-inward, ski-change and angulation-change we produce the specific motion of the skis (inward-drifting and outward-drifting).

By means of leaning-forward and leaning-backward we control the turn of the skis.

By means of varying lateral support we maintain the dynamic balance for the turn.

Important consequences:
No mechanisms of turning

Flattening of skis is in contradiction to the position of the edges, when performing turn.

Unweighting does not fit with the requirement of lateral support of the skier.

Leg rotation is not practicable, because the edges are always directed against the slope.

Stepping (shifting the body weight to the outside ski) is not conceivable, because falling-inward (inclination) is required.
A simple solution

- The sum of the friction forces $F_R$ (external force) eccentrically have an effect on the skis and causes external torques from the slope to the skis.
- It is unmistakenly reality: The slope turns the skis!

A new view – A new understanding

- The slope turns the skis, but we have to establish the appropriate contact between the skis and the slope. We do this by means of the technical elements discussed:
  - by falling-inward, ski-change and angulation-change we vary the edge-angle and thereby the friction force $F_R$.
  - Through leaning forward and backward we vary the distance of the centre of gravity (KSP) from the friction force and thereby the torques from the slope to the skis.
Conclusion

In short:

When performing parallel-turns
- we always do the same!

(G. Kassat, 1985, 1997)

Lever arms and muscles

Effort force and load force are applied on the same side of the axis of rotation
Effort force applied closer to axis than the load \((\text{i.e. } d_{\text{effort}} < d_{\text{load}})\)
Effort and load force act in opposite directions
Good for moving load quickly or through large range of motion; poor for strength
Static equilibrium

A system is at rest and will remain at rest.
No translation or rotation is occurring or will occur.

Conditions for static equilibrium (from Newton's 1st law):
- Net external force in x-direction equals zero
- Net external force in y-direction equals zero
- Net torque produced by all external forces and all external torques equals zero

Can use any point as the axis of rotation.
Can solve for at most three unknown quantities.

\[ \Sigma F_x = 0 \]
\[ \Sigma F_y = 0 \]
\[ \Sigma T = 0 \]

Lecture problem 1

During an isometric (static) knee extension, a therapist measures a force of 100 N using a hand dynamometer in the position shown below.

Find the resultant knee joint force and torque.
Does the dynamometer position affect the measured force?

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Dynamic equilibrium

Applications to rigid bodies that are accelerating

Conditions for dynamic equilibrium
(from Newton’s 2nd law):

Net external force in x-direction equals mass times x-acceleration
Net external force in y-direction equals mass times y-acceleration
Net torque produced by all external forces and all external torques equals moment of inertia times angular acceleration

Net torque must be computed about COM or fixed axis of rotation
Can solve for at most three unknown quantities

\[
\Sigma F_x = m \ a_x \\
\Sigma F_y = m \ a_y \\
\Sigma T = I \ \alpha
\]

Computing joint forces and torques

It is possible to measure:
- joint position (using video/motion capture)
- ground reaction forces (using force platform)
- centre of pressure (using force platform - point of application of ground reaction forces)

From joint position data, we can compute:
- absolute angle of each segment
- location of centre of mass of each segment

Can use central differences method to compute:
- angular velocity of segment
- angular acceleration of segment
- x- and y-velocity of segment COM
- x- and y-acceleration of segment COM

Finally, use general equations of motion to compute joint forces and torques
General equations of motion

From dynamic equilibrium:
\[ \Sigma F_{\text{segment}} = m_{\text{segment}} \ a_{\text{segment}} \]
\[ m \ a_x = F_{dx} - F_{px} \]
\[ m \ a_y = F_{dy} - F_{py} - F_W \]
\[ \Sigma T_{\text{joint/COM}} = I_{\text{joint/COM}} \ \alpha_{\text{joint/COM}} \]
\[ I_{\text{COM}} \ \alpha = -T_d + T_p \\
- (L - c) \sin \theta \ F_{dx} \\
- c \sin \theta \ F_{px} \\
+ (L - c) \cos \theta \ F_{dy} \\
+ c \cos \theta \ F_{py} \]

L = segment length
\( c \) = proximal end to COM

Solutions

<table>
<thead>
<tr>
<th></th>
<th>Ankle</th>
<th>Knee</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_x )</td>
<td>-125N</td>
<td>-125N</td>
</tr>
<tr>
<td>( F_y )</td>
<td>-665.5N</td>
<td>-628.5N</td>
</tr>
<tr>
<td>( T )</td>
<td>128.6N</td>
<td>104.8N</td>
</tr>
</tbody>
</table>

Internal
- Plantarflexor
- Flexor

External
- Dorsiflexion
- Extension
How to solve the dynamic case?

Knee extensor: Kinematic data - no externally measured forces

• InverseDyn_01.xls

So far we have only talked about net joint torque and force:

The 'many muscles' problem?

Solve the muscle recruitment problem:
The effect of ski boot modifications on joint loading during mogul skiing

Uwe G. Kersting
Paul McAlpine, Nico Kurpiers

Background

Freestyle skiing growing remarkably over the past decade
(Babic 2006, Fry 2007)

Injuries affect mainly the knee
(Langran, 2008; Hunter 1999)
... especially in mogul skiing (landings following aerials)
Mechanisms (?)

Intervention possibilities

Effect of equipment on knee joint loading in free-style skiing

Skier-Shoe-Binding-Ski System?

→ Focus: boot shaft
Approach

Detailed mechanical assessment of skiing technique!
segmental movement
external forces and moments
biomechanical models ...

http://www.youtube.com/watch?v=scLlZ5E-zCQ

Outdoors!

Just move the lab outdoors?

Kinematics are manageable by cameras
Force measurement systems have been described - few intervention studies published

6 DOF force sensor

(Niessen et al., 1999)
(Kiefmann et al., 2006)
The Model

Detailed model repository included
Kinematic optimisation/scaling
Inverse dynamics
Optimisation for muscle activation

VL: 93%
VL: >100%

Adaptation to skiing

Upper trunk and arms fixed (in a skiing position)
Subtalar joint axis fixed in neutral position
Forceplates 'attached' to the feet
Boot stiffness added as angle-dependent joint torque
Application

Stiffness function added to ankle model
Application to two boot interventions
1) Wave course:
   (Kurpiers et al. ISSS, 2009)
2) Mogul skiing run:
   (Kurpiers et al., 2011)

A hypothetical application

1 subject, 1 trial
Same kinematics
Same reaction forces
Boot specific stiffness

Stiffness removed
Joint compression force
In real life
9 subjects, 3 trials each, 2 boot conditions
flexible shaft (FL) - standard (stiff) shaft (ST)
Average muscle activation = force
At GRF maximum
69 - 81% muscle force reduction
40% reduction of ankle joint compression

The knee joint!
Knee anterior posterior force

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Results - Muscles

![Graph showing muscle activation and joint force](image1.png)

Results

Example

Right GRF with ap-tibia force

![Graph showing GRF with time](image2.png)
Summary of findings

- Change in the body position
  - Greater range of movement, particularly at ankle joint
  - Forward shift of the CoM at force maximum
- Reduced GRF
- Change in net forces and moments in the ankle and knee joint
  - Reduced anterior tibia force (from 11 BW to 8 BW)
- Reduced muscle activation in the lower extremities
- General acceptance of the modified ski boot by freestyle skiers

Summary

Commonly accepted technique descriptions may be misleading → implications for teaching of sports (skiing) technique

Inverse dynamics to 'inversed' inverse dynamics

Outdoor skiing test setup established

Ankle flexion stiffness of boots alters joint loading at ankle and knee

Future: Inclusion of landing after aerials → most critical

Perspectives for the general skiing community
Thank you!

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