FÉDÉRATION INTERNATIONALE DE GYMNASTIQUE

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FIG ACADEMY

BIOMECHANICS FOR GYMNASTICS

Level 1
Lecture 2
Review of LECTURE 1
1. Principles of stability (4 principles)
2. Correct force application – 5 (6) factors
3. Inertia (Newton’s 1st)
4. Velocity & momentum
5. Acceleration (Newton’s 2nd)
6. Force
7. Action-reaction – 3 factors (Newton’s 3rd)
8. (Ground) reaction forces
Principles of Stability

- **LARGE BASE** vs **NARROW BASE**
  - More stable
  - Less stable
- **Point of falling over**
  - More stable
  - Less stable

Review of Lecture 1 – continued
Effective force application for take-offs, is related to:

- **Magnitude** - strength in all active muscles
- **Point of application** - (for rotation: off-centre force far from axis of rotation)
- **Direction** - always opposite to application
- **Duration** - range of motion/flexibility
- **Timing** - coordination
- **Rigidity of the body** - body tension & shape
Inertia – a body does not want to change what it is doing (its state of rest or motion in a straight line).

Any change means its velocity (momentum) has changed (from 0 or from some existing velocity).

A change in velocity is called acceleration.

A change of velocity requires the application of a force. Therefore acceleration is a measure of the force applied \((F = m \times a) \rightarrow (F \equiv a)\)

If a body slows down, speeds up or changes direction, a force must be the cause.
At the instant of take-off, these are **determined**:

- **Path of centre of mass** (trajectory)
  - Angle of take-off and landing (of C of M)
  - Vertical velocity up (reduced to zero by gravity)
  - Vertical velocity on landing = initial vertical velocity
  - Horizontal velocity
  - Height (= time)
  - Distance
  - Direction

- **Time in the air** (= height)

- **Angular momentum**
  
  *(body shape = potential to change speed of rotation)*

- **Total Mechanical Energy**
  
  *(Total Mechanical Energy = Kinetic Energy + Potential Energy)*

**Most errors occur at take-off and are usually due to incorrect force application.**
For every action force there is a reaction force that is:

- Equal in magnitude
- Opposite in direction
- Simultaneous

Forces always act in pairs

- When the body is in contact or support, the “action – reaction” mechanism is constrained by the external object and this results in an “indirect” force being applied to the object which simultaneously generates an equal and opposite reaction force.

- The trick to much of gymnastics is to optimally generate and time these “indirect” reaction forces perfectly.
Isaac Newton – the master of force

Sir Isaac Newton on British £50 note

Inertia
Acceleration
Action – reaction
Gravitation

A quick look at the magnitude of forces on gymnasts →
Magnitude of External Forces

• Jumping:
  GRF 6 - 8 x BW (Panzer 1984)

• Landing:
  GRF 9 - 15 x BW (McNitt-Gray et al. 1993)
Magnitude of Internal Forces
Joint forces during take-offs and landings

- Tibio-talar joint 23 x BW (~11,000 N)
- Talo-navicular joint 19 x BW (~8,000 N)
- Achilles tendon force 15 x BW (~7,500 N)

Comment:
Joint pressure is close to the upper tolerance limits of the human body.

Bruggeman 2003
### Reaction forces during the support phase of the hands

#### Maximum reaction forces

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Newtons/10 ≈ Kilograms

Schweizer 2002
As soon as a body is in the air the force of gravity continuously acts downward to change its velocity and direction. It **accelerates** downward. Its horizontal velocity remains constant.

Gymnasts cannot alter their flight path (**TRAJECTORY**) when in the air. The centre of mass follows the path of a parabola.
Projectiles

• The Center of Mass will follow the path of a parabola. The shape of the path depends on:
  – 1) Angle of release
  – 2) Height of release
  – 3) Velocity of release

• Therefore, during take-off, the correct parameters are essential.
For any take-off velocity, the angle of take-off from the apparatus will determine the shape of the flight parabola (the trajectory of the CoM).

- A steep take-off angle will produce a high flight with small horizontal travel.
- A shallow take-off angle will produce a low flight with large horizontal travel.
Effect of changing release height

• A centre of mass of a rigid body will fly at a tangent to the arc of the swing (90° to the radius).
• This is an important consideration but gymnasts can apply forces just before release to somewhat modify this effect. In addition, the elasticity of the bar can modify the effect.
At the instant of take-off, these are determined:

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  - Distance
  - Direction

- **Time in the air** (= height)

- **Angular momentum**
  (body shape = potential to change speed of rotation)

- **Total Mechanical Energy**
  (Total Mechanical Energy = Kinetic Energy + Potential Energy)

Most errors occur at take-off and are usually due to incorrect force application.
All human motion is a result of

- Muscle contractions ➤➤➤ Force
- Move body segments ➤➤➤ Accelerates levers
- About joints ➤➤➤ About an axis
Main Concepts in Rotation

MOMENT OF INERTIA (ROTATIONAL INERTIA)
• A measure of the distribution of mass about the axis of rotation.
• If the mass is far from the axis, the Moment of Inertia is large.
• If the mass is close to the axis, the Moment of Inertia is small.

ANGULAR VELOCITY (ROTATIONAL VELOCITY)
• The speed of rotation about the axis of rotation

ANGULAR MOMENTUM (ROTATIONAL MOMENTUM)
• The total quantity of rotation about the axis of rotation
1. Angular Momentum
2. Moment of Inertia & Angular Velocity
3. The conservation of Angular Momentum
4. Generating Angular Momentum

Or, for easier understanding:

1. Rotational Momentum
2. Rotational Inertia & Rotational Velocity
3. The conservation of Rotational Momentum
4. Generating Rotational Momentum
• With a straight body (frame 4 & 5), the distribution of mass is furthest from the transverse axis.
  - Therefore the Moment of Inertia is large relative to the axis of rotation.

• With a tucked body (frame 6 & 7), the mass is brought close to the transverse axis.
  - Therefore the moment of Inertia is small relative to the axis of rotation
  - There is less resistance to a turning motion.
Angular Momentum is **conserved in the air**

Angular Momentum = Moment of Inertia x Angular Velocity

- If total AM on take-off = 80 (see example below), then nothing the gymnast does can change that total.
- But, the gymnast can change body shape which is equivalent to changing the Moment of Inertia.
- In order to conserve the AM, the change in Moment of Inertia (I) must be accompanied by an opposite change in Angular Velocity – the speed of rotation.

Approximate Moments of Inertia of common body positions (kg.m$^2$)

- Total stretch I $\approx 20$
- Pike position I $\approx 6$
- Tight tuck I $\approx 4$

$80 = 20 \times 4$
$= 6 \times \approx 13$
$= 4 \times 20$
Possible Actions in the Air

• Changing body position to change Angular Velocity
  • Asymmetrical body actions to create body tilt (action-reaction)
  • Intersegmental transfer of Angular Momentum (Secondary Axis)

These discussions are for Academy Level 2

Saltos
Twists
Generating Angular Momentum

- Off centre (ground reaction) force
  - Maximum distance from axis
  - Couple/torque

A gymnast must maximize Angular Momentum during the take-off phase in order to maximize the possible effect of changing his body shape.

Torque = Force x distance
Generating angular momentum during take-off (dissipating on landing)

- **Magnitude**: maximum (optimum) off-centre force
- **Point of application**: applied as far as possible from axis of rotation
- **Direction**: always opposite to application
- **Duration**: applied throughout take-off phase
- **Timing**: large to small; proximal to distal
- **Rigidity of the body**: body tension & shape
At the instant of take-off, these are determined:

- **Path of centre of mass** *(trajectory)*
  - Angle of take-off and landing *(of C of M)*
  - Vertical velocity up *(reduced to zero by gravity)*
  - Vertical velocity on landing = initial vertical velocity
  - Horizontal velocity
  - Height *(= time)*
  - Distance
  - Direction

- **Time in the air** *(= height)*

- **Angular momentum**
  *(body shape = potential to change speed of rotation)*

- **Total Mechanical Energy**
  *(Total Mechanical Energy = Kinetic Energy + Potential Energy)*

Most errors occur at take-off and are usually due to incorrect force application.
Generating Angular Momentum

Feet fast forward for large reaction force. Body tall so force acts far from axis.

Arms up creates upward reaction force. Also downward jump and leg extension.

Tight tuck for small Moment of Inertia and large Angular Velocity.

Body straight for maximum Moment of Inertia and brief trunk flexion adds rotational reaction force.

Stretch body for large Moment of Inertia and small Angular Velocity.

Apply forces over maximum time.

Example of Salto Forward
Generating Angular Momentum

Example of Salto Backward
Generating Angular Momentum

Push-up full turn – simultaneous?

Must achieve positions quickly and briefly = physical preparation

What is happening here?
The Take-off phase is critical. Most errors occur here!

The path of the Centre of Mass in flight is determined:

Nothing the gymnast does in the air can change the path of the Centre of Mass.

The total body Angular Momentum in flight is determined:

Nothing the gymnast does in the air can change the Angular Momentum of the body.
Swing

Rotation about an external axis.

1. Mechanics of Swing
Mechanics of rotation (swing)

- The gymnast should maximize (optimize) angular momentum at bottom of swing.
- On downswing, gravity provides the turning force (torque)
  - Gravity should act over longest possible time
  - Gravity should act as far from axis (bar) as possible
  - Gymnast should minimize frictional forces
- On upswing, the angular velocity is increased by bringing the center of mass closer to the axis of rotation (bar)
Mechanics of rotation (swing)

**Downswing**
maximize torque to increase angular momentum

**Upswing**
reduce negative torque to increase angular velocity

\[ A \]

Moment arm
\[ x_1 \]
Axis of rotation

\[ B \]

Moment arm
\[ x_2 \]
Biomechanics of swing with example of giant swing (same for UB, HB, PB)

Max stretch = longest time and distance for gravity to act for max AM

Max stretch = gravity acting max distance from axis = max torque at every instant

**Tap helps with timing and loads the bar. Variations of technique for special purposes.

Bring CoM closer to bar to increase angular velocity and overcome friction

Bar acts as a spring and returns elastic energy
Comparison of Linear & Angular Concepts

- Distance
- Mass (inertia)
- Velocity
- Momentum
- Force
- Acceleration

- Angle (moved through)
- Moment of Inertia
  - Rotational Inertia
- Rotational Velocity
- Rotational Momentum
- Torque
- Rotational Acceleration
Landings

Basically, the reverse of take-offs. Instead of generating forces to gain linear and angular momentum - - - during landings, forces must be applied to reduce all momentum to zero.

1. Absorbing energy. (A full discussion of energy concepts occurs in Level 2.)

2. Reducing the linear and/or angular momentum to zero. (force is not absorbed)

3. Preparation for landing.
Landings & Impact

Short time of impact = large force

Longer time of impact = reduced force
The momentum must be reduced over as long a time as possible.

The energy must be absorbed over the largest area or largest body surface possible.

The energy can be absorbed by softer landing surfaces.

Changing momentum requires the application of forces.
• Most gymnastics landings follow an element with rotation about one or two axes.

• The gymnast must be able to complete the twist or salto and extend the body prior to landing. *(more height (= time) & more angular momentum → better force application during take-off)*

• An extended body position prior to landing reduces the angular velocity and provides time to apply forces that reduce the Angular Momentum to zero. *It also reduces deductions.*
Jump & Land with Turns - Errors

- This full turn is barely a ½ turn
- She pivots +90° before take-off
- She lands with the turn incomplete
- Solutions are all in physical preparation
  - More torque
  - More height
  - Tighter body
- Consider injury possibilities
Effective force application is related to:

- **Magnitude** - eccentric strength in all active muscles
- **Point of application** - far from axis - stop rotation
- **Direction** - always opposite to application
- **Duration** - range of motion/flexibility
- **Timing** - coordination (reverse of take-off)
- **Rigidity of the body** - body tension & shape
Effective force application for **take-offs**, for **landings**, and for generating **angular momentum** is related to:

- Magnitude
- Point of application
- Direction
- Duration
- Timing
- Rigidity of the body
Practical session – application: Safety

Landings in the Gym

Our goal should be to develop

INDESTRUCTIBLE children.

• Landings on the feet – forwards, backwards, sideward
• Landing on the hands – forwards, backwards, sideward
• Landing with horizontal momentum shoulder rolls – forwards, backwards, sideward
• Landing flat on the back - break falls
• Inverted landings
The FIG appreciates the collaborative efforts by expert individuals who have worked to develop these presentations.

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