JOINT MOMENTS IN WATER-SKIING CHILDREN

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INTRODUCTION: The water-skier is a classical biomechanical example of the moment and force equilibrium of two different contact forces (water reaction force and rope force) and the gravitational force. The moment of the water reaction force is controlled by the lower limb joints, the moment of the rope force by the shoulder joints. The aim of this study was to analyze the amount of these moments exerted on these joints in juvenile water-skiers. The purpose was to calculate the amount of the joint moments and to seek differences between experienced water-skiers and beginners.

METHODS: Ten male water-skiers (7-11 yrs) belonging to a local club volunteered for the experiments. Five children were championship skiers, the other 5 were beginners. Photos were taken as the skiers passed perpendicular to the optical axis of the camera. Five trials per child were photographed. The speeds (10 - 20 m/s) were constant (no acceleration) at the time of the photo. The direction of the gravitational acceleration vector was defined, relative to the lake shore, by means of a plumb-line. The skis and the test persons were weighed afterwards and their segment lengths and body height were measured. Body segment parameters were also taken from the literature (Jensen, 1986).
For the 2D model, the free body diagram consisted of the skier, the ski, the bar and the beginning of the rope (Figure 1). The x-axis of the co-ordinate system corresponded to the motion direction, the y-axis pointed upwards. The positions of the joint centers, gravity center of the head, the ski, and the rope, and the direction of the gravitational acceleration were marked on the photographs. The data-sets of the marked items were brought into correct size and imported into a program developed for the mechanical calculations (quasi-static, inverse-dynamic). First, the gravity center of the whole free body diagram was calculated from the single gravity centers of the segments, as well as the lever arms of the rope force relative to the gravity center. The forces of the rope (Rx & Ry) and the ski (water reaction; Sx & Sy) were calculated from the gravitational force (GF) and the inclination of the rope and the ski (relative to GF). The friction force on the ski was considered to be zero. The lever arms of the forces Sx & Sy were then calculated by means of the moment equilibrium, defining the instantaneous center of pressure (ICP) on the ski. Finally, the joint moments (ankle, knee, hip, shoulder) were calculated from the forces Rx, Ry, Sx, Sy, and the segment weights. The joint moments were calculated in relative values (forces per total weight TW, levers per body height BH, magnification 10000; = %TW x %BH). One Newton-meter relative to a TW of 500 N and a BH of 1.5 m corresponds to 13.33 %TW x %BH.

ANALYSIS:

a) Calculation of body weight (BW), ski weight, (SW) and total weight (TW).
BM – body mass, SM – ski mass

$$BW=BM*9.81 \quad (1)$$

$$SW=SM*9.81 \quad (2)$$

$$TW=SW+BW \quad (3)$$

b) Calculation of the position of the gravity center of the whole body (BGX & -Y) and of the free body diagram (SUGX & -Y), considering the mass percentage of the single segments.

COGAX & -Y – gravity center of the whole arm, COGHX & -Y – gravity center of the head, COGTX & -Y – gravity center of the trunk, COGTHIX & -Y – gravity center of the thigh, COGSHAX & -Y – gravity center of the shank, COGFX & -Y – gravity center of the foot, COGSKX & -Y – gravity center of the ski (both skis), AGE – age of the subjects (used for the determination of the mass proportions according to the regression equations of Jensen, 1986)

BGX = COGAX * 2 * (.00099 * AGE + .04567) + COGHX * (-.0114 * AGE +.2376) + COGTX * (-.0006 * AGE + .4246) + COGTHIX * 2 * (.00364 * AGE + .06634) + COGSHAX * 2 * (.00122 * AGE + .03809) + COGFX * 2 * (.00015 * AGE + .0187) (4)

BGY = COGAY * 2 * (.00099 * AGE + .04567) + COGHY * (-.0114 * AGE +.2376) + COGTY * (-.0006 * AGE + .4246) + COGTHIY * 2 * (.00364 * AGE + .06634) + COGSHAY * 2 * (.00122 * AGE + .03809) + COGFY * 2 * (.00015 * AGE + .0187) (5)

SUGX=(BGX*BM + COGSKX*SM)/(BM+SM) (6)

SUGY=(BGY*BM + COGSKY*SM)/(BM+SM) (7)

c) Calculation of forces and force equilibrium

GF – gravitational force, SX & -Y – ski force (water reaction force), RX & -Y – rope force, SIG – ski angle (inclination; in radians), RHO – rope angle (in radians), PI – 3.14159...

GF=-TW (8)

SX=TW/(TAN(PI/2+SIG)-TAN(RHO)) (9)

RX=-SX (10)

RY=RX * TAN(RHO) (11)

SY=-(GF+RY) (12)

d) Moment equilibrium and calculation of the instantaneous center of pressure (ICP) at the ski

FX & -Y – position (end) of the ski, HX & -Y – position (beginning) of the rope, ICPX & -Y – position of the ICP

D=FY-FX*TAN(SIG) (13)

ICPX=(HY*RX-HX*RY-SUGX*GF + D*SX)/(SY-TAN(SIG)*SX) (14)

ICPY=ICPX*TAN(SIG)+D (15)

e) Calculation of the joint moments, considering the contact (rope, ski) forces and the gravitational forces of the body segments

SHOX & -Y – position of the shoulder center, ANKX & -Y – position of the tarsal center, KNEEX & -Y – position of the knee center, HIPX & -Y – position of the hip center, MZSHO – shoulder moment about z-axis, MZANK – ankle moment about z-axis, MZKNEE – knee moment about z-axis, MZHIP – hip moment about z-axis

MZSHO=((HX-SHOX)*RY-(HY-SHOY)*RX-(COGAX-SHOX)*BW*.2*(.00099*AGE+.04567))/2 (16)

MZANK=((ICPX-ANKX)*SY-(ICPY-ANKY)*SX-(COGFX-ANKX)*BW*2*(.00015*AGE+.0187)-(COGSKX-ANKX)*SW)/2 (17)

MZKNEE=((ICPX-KNEEX)*SY-(ICPY-KNEEY)*SX-(COGFX-KNEEX)*BW*.2*(.00015*AGE+.0187)-(COGSHAX-KNEEX)*BW*2*(.00122*AGE+.03809)-(COGSKX-KNEEX)*SW)/2 (18)

MZHIP=((ICPX-HIPX)*SY-(ICPY-HIPY)*SX-(COGFX-HIPX)*BW*.2*(.00015*AGE+.0187)-(COGSHAX-HIPX)*BW*2*(.00122*AGE+.03809)-(COGTHIX-HIPX)*BW*2*(.00364*AGE+.06634)-(COGSKX-HIPX)*SW)/2 (19)

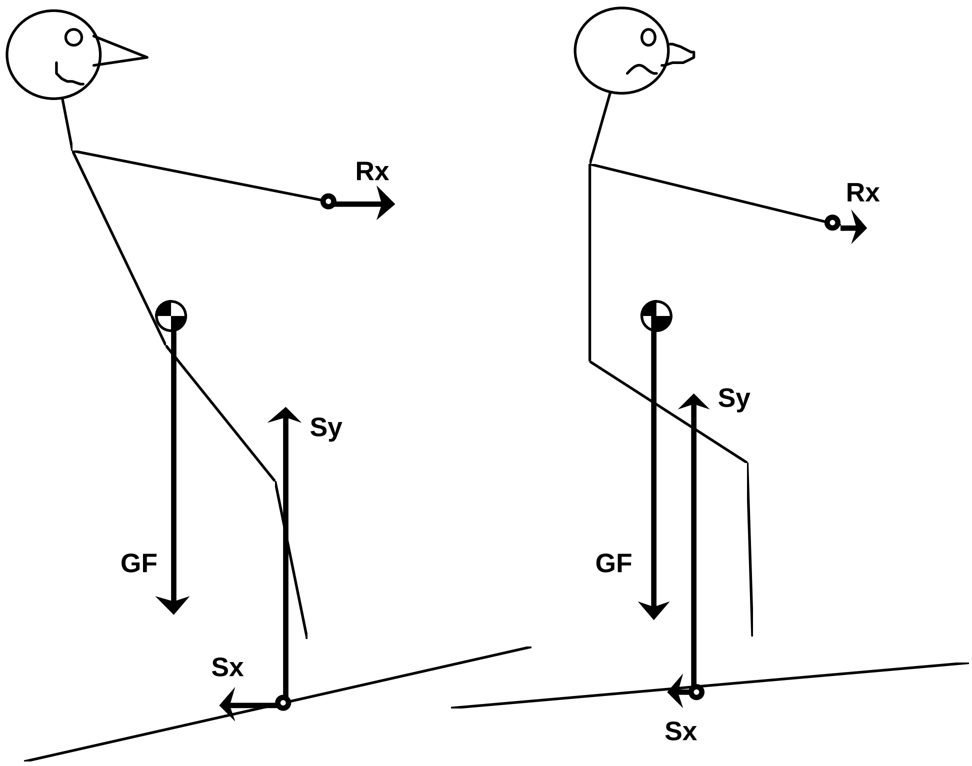

Figure 1 — Stick figure illustration of a skilled skier and a beginner (according to the respective photos), including gravitational and reaction forces, according to formulas (1)-(15).

RESULTS: Experienced skiers moved at higher speeds than beginners and consequently had a more pronounced ski inclination (Figure 1). The magnitude of the joint moments depended on the skiing position (Figure 1). For skilled skiers, moments were far less than for beginners. The moment values for experienced skiers in the shoulder and hip joints were rather low: shoulder – 19±5 %TW%BH tending to retrovert, hip – 9±3 %TW%BH tending to flex. Knee and ankle moments were higher: knee – 276±44 %TW%BH tending to flex, ankle – 253±37 %TW%BH tending to plantarflex. The moment values for beginners were: shoulder – 53±11 %TW%BH tending to retrovert, hip – 177±23 %TW%BH tending to flex, knee – 532±56 %TW%BH tending to flex, ankle – 477±48 %TW%BH tending to plantarflex. The differences between the two groups are significant. The pressure center (ICP) of the water reaction force was at the heel region in skilled skiers, but behind the heel in beginners (Figure 1).

DISCUSSION: The experienced skiers tried to minimize their shoulder and hip moments as far as possible. These moments were rather low and hence can be neglected. The knee and ankle moments of beginners were about twice as high as those of skilled skiers. A further difference can be seen in the location of the pressure center on the ski. The reason for these differences lies mainly in body position: Experienced skiers lean backwards, whereas beginners assume a more squat position. An unexpected result was the direction of the shoulder moment. One would expect that the rope force tends to antevert the arm. The weight of the arm, however, balances and even "outweighs" the rope force, resulting in a small moment tending to retrovert the arm. It should, however, be considered that the analyzed situation occurred at a constant speed. When the boat speeds up, the rope force increases by reaction forces due to inertia, leading to an anteversion moment in the shoulder.

CONCLUSIONS: Joint moments decline as-skiers become more experienced. Improving body position means reducing joint loads.

REFERENCES:

Jensen, R. K. (1986). Body Segment Mass, Radius and Radius of Gyration Proportions of Children. *Journal of Biomechanics* **19**(5), 359-368.