STUDIES IN SPORT, PHYSICAL EDUCATION AND HEALTH 13

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ON THE MECHANICS OF HUMAN MOVEMENT

WITH SPECIAL REFERENCE TO WALKING, RUNNING AND JUMPING

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CONTENTS

PREFACE

This thesis is based on the following studies, which will be referred in the text by their Roman numerals:

I LUHTANEN, P., and P. V. KOMI. Segmental contribution to forces in vertical jump. Europ. J. Appl. Physiol. 38: 181-188, 1978.

II LUHTANEN, P., and P. V. KOMI. Mechanical factors influencing running speed. In: Biomechanics VI-B, edited by E. Asmussen and K. Jörgensen. Baltimore: University Park Press, 1978, p. 23-29.

III LUHTANEN, P., and P. V. KOMI. Mechanical energy states during running. Europ. J. Appl. Physiol. 38: 41-48, 1978.

IV LUHTANEN, P., and P. V. KOMI. Mechanical power and segmental contribution to force impulses in long jump take-off. Europ. J. Appl. Physiol. 41: 267-274, 1979.

V LUHTANEN, P., and P. V. KOMI. Force-, power- and elasticity velocity relationships in walking, running and jumping. Europ. J. Appl. Physiol. in print, 1980.

The studies were carried out at the Department of Biology of Physical Activity, University of Jyväskylä, Finland, with collaboration of several persons to whom I wish to express my sincere gratitude:

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Jyväskylä, June 1980

Pekka Luhtanen

1. INTRODUCTION

Purposeful human movement involves overcoming the external forces influencing the total system in human movement according to physical or mechanical principles. In order to produce an appropriate pattern of movement for the accomplishment of a particular goal, it is necessary for the performer to overcome the biomechanical constraints such as mass, gravity and inertia that impose themselves upon the organization of the movement.

The laws of inertia, acceleration and reaction provide the theoretical basic support for important biomechanical constructs. One important construct in short maximal performances is the summation of internal forces, which means the optimization or maximization of generated muscular force through successive body segments in time and space at the points of impact or point of greatest strength within a kinematic chain of movement. The force exerted during contact with the ground is linked with the center of gravity of the total body by a system of bones, joints, muscles and tendons. For mechanical analytical purposes this system is often considered to be one of rigid segments linked by pin joints.

As a mechanical unit the muscle is a damped oscillator including viscoelastic forces (Levin and Wyman 1927, Hill 1938). Hill (1949) proposed a model for the skeletal muscle, which divided mechanical properties of the muscles into three elements: an active contractile element representing the processes by which the muscle responds to stimulation, and two passive elastic elements, a series elastic element and a parallel elastic element. The instantaneous length of both elastic elements determines force.

The force production of muscles depends on the following mechanical and dynamic properties: cross-sectional area (Morris 1948, Ikai and Fukunaga 1968), EMG-activity (eg. Lippold 1952, Bigland and Lippold 1954), contraction time (eg. Wilkie 1950, MacPherson and Wilkie 1954, Royce 1962, Chapman 1974, Viitasalo and Komi 1977), movement velocity (Wilkie 1950, Asmussen et al. 1965, Komi 1973, Pertuzon and Bouisset 1973, Bosco and Komi 1979), Compliance of muscle (Goubel et al. 1971) and joint (Gottlieb and Agarwal 1978), temperature (eg. Hill 1951, Clarke and Royce 1962, Asmussen et al. 1976), muscle length (Gordon et al. 1964) and joint angle (eg. Carpenter 1938, Lindeburg 1964, Singh and Karpovich 1966, Komi 1973).

In addition, the central and peripheral nervous systems are active during movement controlling and coordinating the functions of different muscles and muscle groups for purposeful performance. The regulation of electrical activity and tension in muscles can be influenced by reflex activities of golgi tendon organ (eg. Denny-Brown 1928, Eccles et al. 1957, Houk and Simon 1967, Stuart et al. 1970, Simons and Dimitrijevic 1972), muscle spindel (eg. Granit 1950, Granit et al. 1957, Granit 1968, Grillner and Udo 1971) and joint receptors (eg. Burgess and Clark 1969, Grigg 1975, Grigg and Greenspan 1977). In different performances the voluntary and reflex mechanisms of the human motor system interact in a rather complex way including alternation of activation and inhibition in agonist and antagonist muscles (eg. Gottlieb et al. 1970, Mellvill-Jones and Watt 1971).

Maximum speed at the center of gravity in different movements is achieved and maintained by the successive summation of forces, moments of force, velocities or other mechanical contributions of segments. In walking, running and jumping at maximum speed with maximal propulsive force the sum of the forces of successive segments should be applied in the direction of the intended movement.

For movements requiring maximum speed this involves initiating the movements of segments in the kinematic chain with optimal radius relative to the center of gravity of the total body. The concept of transfer of force and speed to succeeding segments is especially significant for the coordination and regulation of movement. The programming of movements of support and stability subsequently leads to the programming of the limb movements that achieve the precision of movement at the correct moment in time and space.

In cyclic movements the foreward velocity is a function of step length and step frequency (Högberg 1952a, Hoshikawa et al. 1971, Nelson et al. 1972, Ballreich 1976). The stepping pattern is different in the acceleration phase, constant velocity and deceleration phase (Cavagna et al. 1971, Murase et al. 1976). In addition the curvature of the track influences the stepping pattern in running.

In human movement man is doing mechanical work to displace body segments forwards-backwards, down-up, laterally, and to rotate them (Fenn 1930b, Elftman 1940, Norman et al. 1976). Oxygen consumption measurements have been used to evaluate the amount of chemical energy used and the efficiency of human machinery during different types of performance. The physiological cost of work can be estimated accurately by the measurement of oxygen consumption during work and recovery. Factors influencing energy consumption are intensity of work due to the velocity of movement (Fenn 1930b, Högberg 1952b, Knuttgen 1961, Margaria et al. 1963, Pugh 1970), type of work (Asmussen 1953, Cavagna et al. 1965), number of active muscles (Furusawa et al. 1927a), fiber composition of active muscle fibers (Karlsson et al. 1968, Gollnick et al. 1974, Secher and Nygaard Jensen 1976) and muscle coordination (Miyashita et al. 1973).

In calculating the mechanical efficiency of work the main problem is the computation of mechanical work. In walking and running this has been calculated through the simultaneous measurements of force and distance covered (Furusawa et al. 1927b), applications of force-platforms (Fenn 1930a) and accelerometers (Cavagna et al. 1963, 1964). Techniques of film analysis have also been utilized (Fenn 1930b, Elftman 1940, Cavagna et al. 1963, 1964, Norman et al. 1976). Slight deviation in calculations of work according to the segmental changes of mechanical energies is due to the different body segment parameters for segmental masses, centers of gravity and moments of inertia (Fisher 1906, Dempster 1955, Hanavan 1964). In film analysis studies the performance is transferred, through different recording methods of certain joint actions, for computer analysis. Because of small deviations from exact space information some data smoothing has been used. For the smoothing of pathways of segmental centers of gravity several methods have been applied including polynomial curve fitting based on the Chebyshev least square approximation (Kuo 1965, Plagenhoef 1968), finite difference method based on Taylor series expansions (Miller and Nelson 1973), cubic spline function (Zernicke et al. 1976) and the second order, recursive Butterworth digital filter (Winter et al. 1974). Comparisons of the above mentioned methods have also been carried out (Pezzack et al. 1977).

Due to different definitions, measuring methods, measuring times, type of work and external conditions, mechanical efficiency has varied from 22.7 % to 75.0 % (Furusawa et al. 1927b, Cavagna et al. 1964, Margaria 1968, Pugh 1971, Lloyd and Zacks 1972, Asmussen and Bonde-Petersen 1974b, Norman et al. 1976, Cavagna and Kaneko 1977).

The output of different cyclic performances can be explained by simple and complex physical quantities. Using only the methods of force platform and film analysis the mechanism of human machinery cannot be described accurately. However, it seems possible to build up a descriptive collection of kinematic and kinetic variables in walking, running and jumping with regard to the movement of different body segments and the center of gravity of the total body.

Therefore the purpose of the present work has been to study

1. velocity, stride rate, length and time characteristics relationships in maximal walking, running, long jump, triple jump and submaximal running,
2. mechanical energy states and power outputs in vertical jump, walking, running and long jump,
3. segmental contributions to force and force impulses in vertical jump, walking, running and long jump, and
4. elasticity-velocity relationships in running, long jump and triple jump

applying a comprehensive motion analysis system for 2-dimensional movements, ignoring lateral movement and rotation about the long axes of segments.

In general, Problem 1 has been dealt with in papers II, IV and V, Problem 2 in papers III, IV and V, Problem 3 in papers I, II and IV and Problem 4 in paper V. Some additional and connective analysis has also been performed.

2. RESEARCH METHODS

2.1. Subjects

The subjects were 24 adult men. Their sport events and physical characteristics are presented in Table 1. All subjects were highly skilled in their respective sport events. In the vertical jump study the subjects were six volley-ball and two basketball players. In the track and field athlete group the subjects were one hammer thrower, one decathlonist, one high jumper, one long jumper and two sprinters. The long and triple jumpers were specialists.

Table 1. Physical characteristics of the subjects.

Group	Number of subjects	Mass (kg)	Height (m)	Performances
Volley- and basketball players	8	72.8 ± 3.5	1.83 ± 0.03	Vertical jump
Track and field athletes	6	81.7 ± 4.1	1.86 ± 0.03	Walking, running and long jump
Long jumpers	4	76.6 ± 2.2	1.84 ± 0.02	Long jump
Triple jumpers	6	73.5 ± 2.1	1.82 ± 0.03	Triple jump

2.2. Procedures

Vertical jump, walking, running and long jump were performed in an indoor hall. The take-off board in vertical and long jump and analyzed step contact was always a force-platform with natural frequency of 100 Hz (Komi et al. 1974). The force-platform was used to record vertical and horizontal ground reaction forces which were stored on magnetic tape (Philips Analog 7 Tape Recorder). Each performance was filmed with a Locam 51-0003 camera set to operate at 100 frames per second. The run-up track was of the tartan type in the studies performed indoors and also in the triple jump performed outdoors in an official competition. The triple jump was filmed by Bolex H 16 Reflex camera at a frame rate of 48 pictures per second.

In the film analysis with a Vanguard film analyzer the mechanical model of a subject was assumed to consist of 7 or 13 rigid segments with the head and trunk forming one segment. The individual segment parameters were obtained using the standards given by Dempster (1955). The necessary x-y coordinates were punched onto paper tape for subsequent computer analysis. Force data from force-platform and film analysis data were analyzed with HP 2116C, HP 21MX, Honeywell 1644 computer and HP 9810A desk computers. The segmental landmarks were marked on the skin with black and white tapes. The equations of joint landmarks for segmental movements were smoothed via 9th degree polynomial curve fitting (Kuo 1965). Velocities and acceleration were derived from these equations.

2.3. Physical methods and formulas

Step lengths were measured both on the spot and evaluated from film analysis. Step rates were calculated from film analysis using the formula:

$$v_x = lf \qquad (1)$$

where v_x = horizontal velocity of the center of gravity
l = step length, and
f = step rate

The change of velocity in running was calculated from equation 2 as follows (Ballreich 1976):

$$(v_x \pm \Delta v_x) = (l \pm \Delta l)(f \pm \Delta f) \quad (2)$$

where Δv_x = change of horizontal velocity
Δl = change of step length, and
Δf = change of step rate

In comparing the contribution of the different body segments with total performances both the force-platform and film analysis techniques were employed. The analysis of the release velocities for the centers of gravity was done in vertical jumps according to the equivalence of force impulse and linear momentum as follows:

$$\int_0^{t_1} (Fy-G)\,dt = m(v_{y1} - v_{y0}) \quad (3)$$

where F_y = vertical force
G = weight of subject
m = mass of subject
v_{y1} = vertical release velocity, and
v_{y0} = 0

To obtain the reaction forces and relative contribution to the total force of the 13 body segments in the phase when maximum forces were produced, the following basic laws of dynamics were used:

$$F_{x_{ij}} = \sum_{i=1,\ j=1}^{13,n} F_{x_{ij}} = \Sigma m_i\, a_{x_{ij}} \quad (4)$$

$$F_{y_{ij}} = \sum_{i=1,\ j=1}^{13,n} F_{y_{ij}} = \Sigma m_i\, (a_{y_{ij}} + g) \quad (5)$$

where Fx_{ij} = whole body horizontal net force in frame j
m_i = mass of segment i
ax_{ij} = horizontal acceleration of a segment i in frame j
Fy_{ij} = whole body vertical net force in frame j
ay_{ij} = vertical acceleration of segment i in frame j, and
g = gravitational constant, 9.81 m/s^2

The role of the different body segments was evaluated using the equivalence of the force impulse, $\int_0^t F_i t \, (dt)$, and the change of linear momentum, $m_i(v2_i - v1_i)$ in the horizontal and vertical direction during the ground contact of various performances:

$$\int_0^t F_i(t)\, dt = m_i(v2_i - v1_i) \qquad (6)$$

where $F_i(t)$ = force of segment i
t = contact time
m_i = mass of segment i, and
$v2_i - v1_i$ = change of velocity of segment i during contact

The total work (positive and negative) performed in different tasks was calculated through the kinetic, rotational and potential energy states using the methods and formulas reported by Norman et al. (1976) as follows:

$$W = \sum_{i=1}^{13} \sum_{j=1}^{n} |\Delta m_i g h_{ij}| + |\Delta \tfrac{1}{2} m_i v_{ij}^2| + |\Delta \tfrac{1}{2} I_i \omega_{ij}^2| \qquad (7)$$

where W = total work
n = number of frames
m_i = mass of segment i
g = 9.81 m/s^2
I_i = moment of inertia of segment i about mass center
h_{ij} = vertical position of segment i in frame j
v_{ij} = linear velocity of segment i in frame j, and
ω_{ij} = angular velocity of segment i in frame j

The positive and negative work were calculated for the contact period in all performances. During the contact period the phase of negative work was taken from the first contact to the position where the C.G. has passed the vertical line through the ankle joint (Cavagna et al. 1964).

The mechanical power per mass unit was calculated through the changes of the kinetic (ΔE_{kin}), rotational (ΔE_{rot}) and potential (ΔE_{pot}) energy states and contact times. Except for walking, the obtained time was the total step cycle. Mechanical power per mass unit ($\bar{\dot{W}}$) was then

$$\bar{\dot{W}} = \frac{\Delta Ekin + \Delta Epot + \Delta Erot}{m \cdot t} \qquad (8)$$

where m = mass of the subject
t = contact time

The mathematical model of hopping presented by Alexander and Vernon (1975) was modified for running and jumping. It has been assumed that the center of gravity was oscillating in both the eccentric and concentric phase harmonically as part of some harmonic motion.

The elasticity of the support leg was evaluated using an apparent spring constant k. When horizontal displacement during contact is $x = \pm b$, the leg has its maximum length, which is $\sqrt{h_i^2 + b_i^2}$. When x = 0, the leg has its minimum value, which is $h_i - \Delta y_{1i}$. Then the apparent spring constant is

$$k = \frac{\pi mg\ (a_i + b_i)}{2b_i\ \left[\sqrt{h_i^2 + b_i^2} - (h_i - \Delta y_{1i})\right]} \qquad (9)$$

where m = mass of subject
a_i = horizontal distance from contact to the highest point
b_i = horizontal distance from the lowest point to beginning or end of contact

h_i = height of the center of gravity during the beginning or end of contact

$\Delta y1_i$ = vertical change of the center of gravity during contact

The effect of the mass of subject was eliminated by dividing the value of k by the mass.

2.4. Statistics

Ordinary statistical methods were used to calculate mean, standard deviation (SD) and standard error (SE). The accuracy of methods has been evaluated including error of measurement in basic quantities: displacement, time and mass (Luhtanen and Saukkonen 1976). Respective errors were ± 1.1 %, 1 % and ± 0.1 %. Differences in segmental masses comparing different body segment parameters can exhibit a variation of 5.0 %. Retest in running (m = 97.0 kg, v = 8.0 m/s) gave differences in maximum of horizontal velocity of ± 1.2 %, in vertical velocity, ± 6.0 %, in horizontal force, ± 2.7 % and in vertical force, ± 3.8 %. These results included all phases of data processing.

In vertical jumps a comparison of maximum force of force-platform recordings with film analysis data showed a maximum deviation of 12.0 % in forces.

The statistical significance of differences was tested by means of students' t-test for paired and unpaired samples and for correlation coefficients. In running, analysis of variance of dependent variables for repeated measurements was used. The significance was tested by the F-ratio. The level of significance was indicated with p-values.

3. RESULTS

3.1. Velocity, stride rate, length and time characteristics in walking, running, long jump and triple jump (Papers II, IV and V)

In maximal normal and race walking horizontal average velocities were 3.19 ± 0.13 m/s and 3.70 ± 0.43 m/s (Figure 1). In race walking the higher velocity ($p < .05$) was attained using a higher step rate (3.15 ± 0.16 Hz) than in normal walking (2.83 ± 0.06 Hz). Step lengths were similarly 1.17 ± 0.02 m and 1.13 ± 0.03 m, respectively.

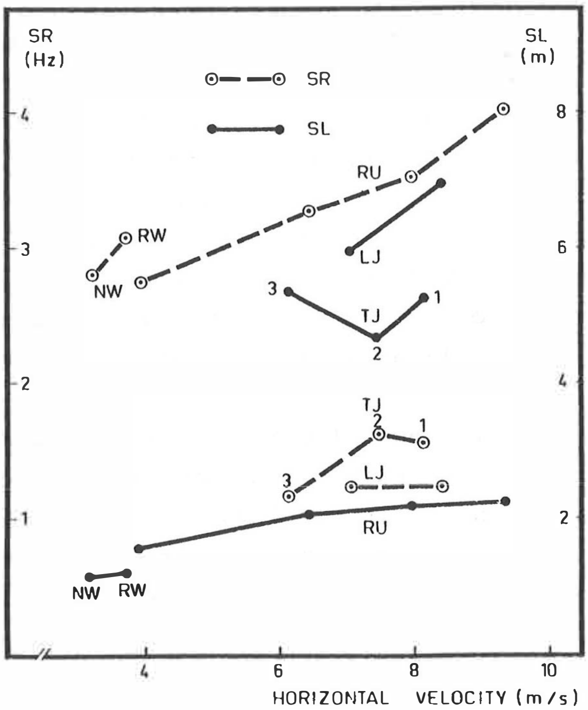

Figure 1. Stride length (SL) and stride rate (SR) in normal walking (NW), race walking (RW), running (RU), long jump (LJ), and triple jump (TJ) step by step (1, 2, 3) at different velocities.

In running the horizontal velocity (3.91 ± 0.28 m/s, 9.30 ± 0.10 m/s) correlated with step rate (2.67 ± 0.06 Hz, 4.03 ± 0.12 Hz) and step length (1.48 ± 0.09 m, 2.25 ± 0.09 m) significantly ($p < .001$). For both variables the parabolic curve fitting was better than the linear one. The increase of running velocity occurred at lower velocities mainly by increasing step length. When the velocity was about 70 % of maximum both step rate and step length influenced the change of velocity equally. At higher velocities the increase of velocity was due to the increase of step rate.

In long jump and triple jump the consecutive step cycles are not so symmetrical as in walking and running. Therefore step rates and lengths are like apparent quantities. In long jump the specialists (6.95 ± 0.15 m) jumped significantly ($p < .01$) longer than the non-specialists (5.92 ± 0.22 m). The step rates are similar because of the different actual velocities.

In triple jump the consecutive steps (1, 2, 3) were performed at lowered velocities with step lengths 5.26 ± 0.12 m, 4.68 ± 0.14 m and 5.37 ± 0.02 m and step rates 1.55 ± 0.03 Hz, 1.61 ± 0.04 Hz and 1.17 ± 0.02 Hz. The relative step lengths including contact foot were 34 ± 2 %, 31 ± 2 % and 35 ± 2 % of the total length (15.37 ± 0.42 m).

Figure 2 presents contact times (except in walking, the time of one step) divided into eccentric and concentric phases of the support leg in walking, running and long jump. In triple jump there are only consecutive contact times. In both types of walking the time of one cycle was 0.34 s with higher deviation in race walking. The relative eccentric phases were, in normal walking, 37 ± 2 % and in race walking, 37 ± 3 % of the total time.

In running, contact times shortened significantly ($p < .001$) from 0.200 ± 0.010 s (v_x = 3.91 ± 0.28 m/s) to 0.110 ± 0.004 s (v_x = 9.30 ± 0.10 m/s). The negative contact time was 35 % and 33 % of total contact time at the lowest and maximum speed, respectively.

In long jump the specialists used higher run-up and release velocities than non-specialists. Due to the different velocities the contact time of specialists (0.110 ± 0.004 s) was significantly shorter ($p < .001$) than the time of non-specialists (0.130 ± 0.004 s). In horizontal direction the time of the negative phase from the total contact phase was 46 ± 1 % in the specialist group and 42 ± 1 % in the ordinary group. The corresponding values in the vertical direction were 5 ± 1 % and 8 ± 1 %.

In triple jump consecutive contact times were 0.127 ± 0.006 s, 0.173 ± 0.005 s and 0.195 ± 0.005 s with average velocities 8.36 ± 0.15 m/s, 7.61 ± 0.21 m/s and 6.46 ± 0.15 m/s, respectively. The corresponding relative times of negative phase were 34 ± 3 %, 35 ± 6 % and 39 ± 4 %.

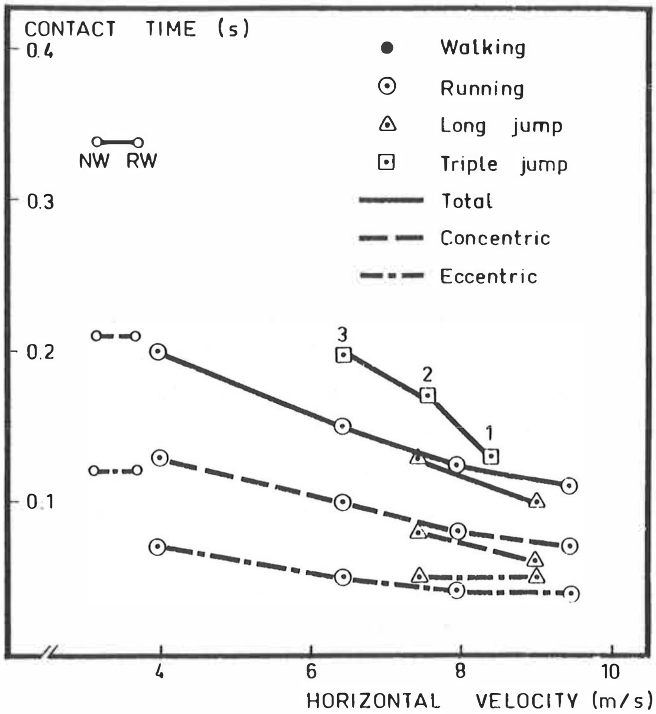

Figure 2. Mean times of various phases of step contact in walking, running, long jump, and triple jump step by step (1, 2, 3) at different velocities.

3.2. Mechanical power and energy states in vertical jump, walking, running and long jump (Papers III, IV and V)

Table 2 presents total mechanical power ($\bar{W}_{tot}$) values divided into energy forms as follows: kinetic ($\bar{W}_{kin}$), potential ($\bar{W}_{pot}$) and rotational ($\bar{W}_{rot}$). The relative values of different energy levels are equal to power values, because the times for single performances are equal for all types of energies.

Table 2. Mechanical powers with energy levels and positive- negative work ratios with average horizontal velocity ($\bar{x}$ ± S.E.) during contact in different performances.

	v_x (m/s)	$\bar{W}_{tot}$ (W/kg)	$\bar{W}_{kin}$ (W/kg)	$\bar{W}_{pot}$ (W/kg)	$\bar{W}_{rot}$ (W/kg)	$\bar{W}_{pos}$ (%)	$\bar{W}_{neg}$ (%)
Vertical jump	-	37.7 ± 2.5	18.3 ± 1.6	13.6 ± 0.9	5.9 ± 0.8	100	0
Normal walking	3.2 ± 0.1	7.5 ± 0.9	6.1 ± 0.9	0.7 ± 0.1	0.8 ± 0.1	63 ± 2	37 ± 2
Race walking	3.7 ± 0.2	14.6 ± 2.9	12.6 ± 2.5	0.8 ± 0.3	1.08 ± 0.2	63 ± 4	37 ± 3
Running	3.9 ± 0.3	20.2 ± 1.3	11.4 ± 1.3	5.4 ± 0.6	3.4 ± 0.4	67 ± 1	33 ± 1
- " -	6.4 ± 0.2	32.7 ± 3.8	21.5 ± 3.7	5.4 ± 0.5	5.8 ± 0.3	66 ± 2	34 ± 2
- " -	8.0 ± 0.1	39.0 ± 3.7	28.3 ± 3.3	5.0 ± 0.5	5.8 ± 0.8	67 ± 1	33 ± 1
- " -	9.3 ± 0.1	49.7 ± 5.3	36.4 ± 3.7	5.0 ± 0.8	8.4 ± 0.7	66 ± 2	34 ± 1
Long jump (non-specialists)	7.5 ± 0.1	126.0 ± 12.6	93.9 ± 12.7	18.9 ± 1.4	13.2 ± 1.8	58 ± 1	42 ± 1
Long jump (specialists)	9.0 ± 0.2	160.1 ± 10.5	122.8 ± 10.5	18.5 ± 1.7	17.7 ± 1.6	54 ± 1	46 ± 1

In vertical jump without preparation movements the total mechanical power output was 37.7 ± 2.5 W/kg. The relative mechanical energy states were 48 ± 8 % for kinetic, 36 ± 5 % for potential and 16 ± 3 % for rotational energies.

In normal walking the total power output was 49 % lower than in race walking although the velocity was only 14 % lower. The major energy level was the kinetic one. Absolute energy levels in potential and rotational forms were similar.

In running and long jump the results were calculated from contact time. In running with progressive velocity (from 3.9 ±

0.3 m/s to 9.3 ± 0.1 m/s) total mechanical power per mass unit increased from 20.2 ± 1.3 W/kg to 49.7 ± 5.3 W/kg ($p < .001$). The relative role of the kinetic energy form increased from 56 % to 73 % ($p < .001$) but the potential energy decreased from 27 % to 10 %. The average proportion of rotational energy level was 16 ± 1 %.

In long jump the total mechanical power of specialists was 160.1 ± 10.5 W/kg and the power of non-specialists 126.0 ± 12.6 W/kg. Most of total work was done in order to change the linear velocity during contact. The proportions of kinetic energy state were 77 % among specialists and 75 % in the non-specialist group. Absolute values in potential and rotational energy forms were similar between 13.2 ± 1.8 W/kg and 18.9 ± 1.4 W/kg.

3.3. Total force production and segmental contribution to force and force impulses in vertical jump, walking, running and long jump (Papers I, II, IV and V)

Force production during performance can be described using instantaneous forces, resultant forces and force impulses joint by joint, segment by segment or for the total body mass center.

The relationships between maximal resultant force and horizontal velocity for different activities were, in maximum walking with normal gait, 478 ± 64 N and in race gait, 537 ± 59 N (Paper V).

When the running velocity changed from 3.9 ± 0.3 m/s to 9.3 ± 0.1 m/s, the resultant force increased from 1081 ± 44 N to 1633 ± 254 N. In long jump the average velocities during contact were 7.6 ± 0.3 m/s for non-specialists and 9.0 ± 0.2 m/s for specialists. The corresponding resultant forces were 2010 ± 80 N and 3270 ± 74 N. When a person did not move horizontally in vertical jump the maximal force was 1005 ± 93 N (Paper I). Vertical jump showed that in total performance knee extension and plantar flexion of the ankle were the most important joint functions in order to attain high release velocity. This conclusion is based on the force impulse analysis in partial movements of the vertical jump.

The force impulse combines force production and time of force together. In vertical jump the total force impulse was 220.2 ± 11.9 Ns. The relative shares of segments were 11 % for arms, 72 % for head and trunk and 18 % for legs. Significant differences in horizontal impulses in cyclic motions are shown in Table 3. In race walking the horizontal impulses of arms ($p < .01$), trunk and head ($p < .05$) and support leg (n.s.) were accelerating segments compared with the action of same segments in normal walking. The role of the swing leg was the reverse (n.s.).

Table 3. Horizontal and vertical impulses of body segments ($\bar{x}$ ± S.E.) during contact at average horizontal velocities (v_x) in different performances.

		Horizontal impulse (Ns)				Vertical impulse (Ns)			
	v_x	Arms	Trunk and head	Support leg	Swing leg	Arms	Trunk and head	Support leg or legs	Swing leg
Vertical jump	-	-	-	-	-	23.5 ± 1.2	157.8 ± 6.4	38.9 ± 2.5	-
Normal walking	3.2 ± 0.1	-0.4 ± 2.1	-3.8 ± 2.9	-4.5 ± 17.4	4.0 ± 14.2	0.2 ± 0.4	-0.4 ± 1.8	0.2 ± 0.3	0 ± 0.5
Race walking	3.7 ± 0.2	12.0 ± 1.9	12.5 ± 4.9	24.2 ± 16.9	-20.3 ± 16.3	-3.5 ± 1.4	0.1 ± 3.3	-1.4 ± 0.7	-2.5 ± 0.9
Running	3.9 ± 0.3	-1.9 ± 1.0	-0.4 ± 1.5	-15.9 ± 5.5	13.1 ± 3.3	1.9 ± 0.8	4.5 ± 1.6	5.5 ± 1.9	-6.2 ± 1.5
- " -	6.4 ± 0.2	-0.5 ± 1.8	4.8 ± 3.2	-16.0 ± 4.4	16.9 ± 6.8	1.1 ± 0.6	4.8 ± 3.4	9.1 ± 1.5	-7.7 ± 2.0
- " -	8.0 ± 0.1	-3.5 ± 2.3	-2.2 ± 4.4	-19.6 ± 5.5	12.0 ± 6.6	3.4 ± 1.3	5.3 ± 4.0	2.3 ± 1.6	-4.5 ± 3.1
- " -	9.3 ± 0.1	-4.7 ± 2.3	-1.5 ± 4.9	-20.3 ± 4.9	33.9 ± 4.9	2.4 ± 1.2	4.8 ± 3.0	5.7 ± 2.4	-7.9 ± 4.5
Long jump (non-specialists)	7.5 ± 0.1	-14.1 ± 3.9	-40.2 ± 10.1	-62.5 ± 11.8	34.5 ± 4.7	31.3 ± 2.0	92.2 ± 12.9	50.1 ± 5.5	42.0 ± 11.2
Long jump (specialists)	9.0 ± 0.2	-17.3 ± 2.5	-26.2 ± 5.0	-36.6 ± 4.8	-20.3 ± 3.1	34.6 ± 1.9	111.8 ± 4.1	33.6 ± 2.5	32.6 ± 3.0

In slow running horizontal impulses were more similar to normal walking than to race walking. Significant differences were in the action of arms ($p < .001$), trunk and head ($p < .05$) and the support leg ($p < .05$). In vertical impulses differences were found in the use of the support leg ($p < .05$) and the swing leg ($p < .01$). Subjects were not skilled in race walking. In running with progressive speed during maximal resultant forces the horizontal force of the support leg, trunk and head were positive (n.s.) but the role of arms ($p < .01$) and the swing leg were negative. Considering total contact time the swing leg increased its velocity, but the role of the support leg was decelerating. In running vertical impulses were positive except in the case of the swing leg. The comparison of maximal running and long jump showed that in long jump all vertical impulses were significantly higher ($p < .001$) than in running within the same subjects. In horizontal impulses there were differences in the use of trunk and support leg. Both segments decelerated more in the long jump ($p < .05$).

In long jumps there were statistical differences between specialists and non-specialists in the horizontal impulses of the swing leg ($p < .001$) and in the vertical impulse of the support leg ($p < .05$).

3.4. Elasticity-velocity relationship in running, long jump take-off and triple jump

Table 4 presents apparent spring constant values in running and jumping for the eccentric and concentric phases of a step cycle. Generally, spring constant values are much higher in the eccentric phase than in the concentric phase.

The highest values of the apparent spring constant of the support leg in the eccentric phase were, in long jump specialists, 30.54 ± 8.38 N x mm^{-1} x kg^{-1} with a horizontal velocity of 9.0 ± 0.2 m/s. The lengths of these jumps were 6.95 ± 0.15 m. In the non-specialist group all values were lower: 13.97 ± 1.01 N x mm^{-1} x kg^{-1}, 7.5 ± 0.2 m/s and 5.92 ± 0.22 m, respectively. During running the average spring constant in the eccentric phase was 0.65 ± 0.06 N x mm^{-1} x kg^{-1} at a velocity of 6.9 ± 0.4 m/s. In triple jumps the vertical displacements of the center of gravity during ground contact were large and the spring constant values relatively low. The highest value (0.58

± 0.11 N x mm^{-1} x kg^{-1}) was found during the first step and the lowest (0.33 ± 0.05 N x mm^{-1} x kg^{-1}), during the last step. The velocities during contacts decreased from 8.4 ± 0.2 m/s to 6.5 ± 0.2 m/s. The spring constant values during the concentric phase were always lower than in the eccentric phase and variability was smaller. The largest difference in the spring constant values was in the long jump specialist group from 30.54 ± 8.48 N x mm^{-1} x kg^{-1} to 0.13 ± 0.01 N x mm^{-1} x kg^{-1}.

Table 4. Apparent spring constants ($\bar{x}$ ± S.E.) in running and jumping for the eccentric and concentric phases of the step cycle at different velocities.

Performance	v_x (m/s)	k^*_{ecc} ($Nxmm^{-1}xkg^{-1}$)	k^*_{conc} ($Nxmm^{-1}xkg^{-1}$)	Number of subjects
Running (m = 81.7 ± 4.1 kg)	6.9 ± 0.4	0.65 ± 0.06	0.13 ± 0.01	6
Long jump, specialists (m = 76.6 ± 2.2 kg)	9.0 ± 0.2	30.54 ± 8.38	0.13 ± 0.01	4
Long-jump, non-specialists (m = 81.7 ± 4.1 kg)	7.5 ± 0.1	13.97 ± 1.01	0.09 ± 0.003	6
Triple jump, (m = 73.5 ± 2.1 kg) step: 1	8.4 ± 0.2	0.58 ± 0.11	0.22 ± 0.03	6
2	7.6 ± 0.2	0.54 ± 0.13	0.11 ± 0.02	6
3	6.5 ± 0.2	0.33 ± 0.05	0.12 ± 0.01	6

Figure 3 presents individual spring constant values from different support phases in running, running long jump take-off and triple jump. The best performances were selected from different events and the long jump take-off of the fastest runner of the non-specialists in long jump (l = 5.78 m) was also used.

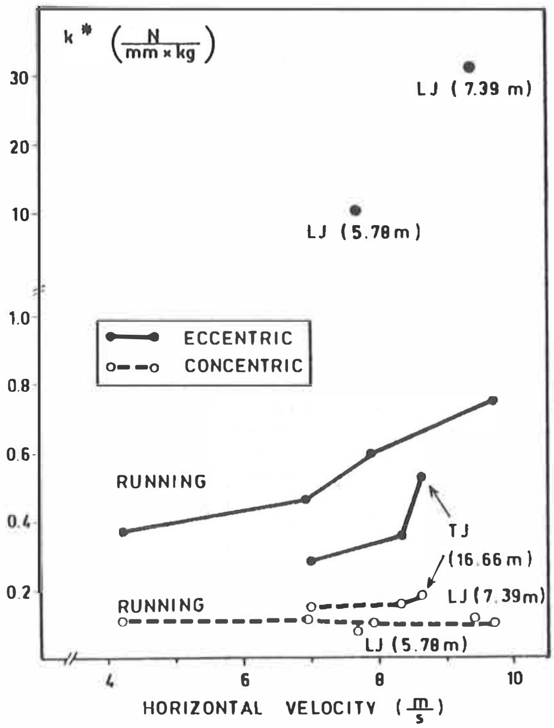

Figure 3. Apparent spring constants of the support leg during the eccentric and concentric phases of running, long jump and triple jump performed at different horizontal velocities.

In running the trend of the apparent spring constant in the eccentric phase is non-linear. The same phenomenon can be seen in the eccentric phase of consecutive step contact in triple jumps. In the concentric phase of running and running long jump take-offs these coefficients were about constant. Only in triple jump a slight parabolic trend can be observed.

4. DISCUSSION

In order to explain the mechanics of human movement one has to take into account several individual direct and indirect factors influencing the output of different maximal performances. Important factors are the voluntary neuromuscular mechanism and reflex functions, the histochemical structure of muscles, the force-length relationship of muscles, joint angles and mechanical properties including elasticity of bones, tendons and muscles. To find a complete solution to maximal or optimal physical performance with respect to the above mentioned properties is a very complex task.

The total mechanism of human machinery cannot be described exactly by means of 2-dimensional film analysis and the force-platform technique. Results indicate, indirectly, timing and force production of different muscle groups by known mechanical variables in different muscle exercises or sport events. In this research the focus was on vertical jumping, walking, running, long jumping and triple jumping, which were studied by combined physical quantities. In different events the main problem was to study the mechanics of maximal performances and submaximal running without muscle fatigue and compare mechanical power output and factors affecting the power output.

In running maximal velocity was attained by increasing both step rate and step length. The relationships between step rate and velocity as well as between step length and velocity were parabolic, in line with earlier studies (Högberg 1952a, Sinning and Forsyth 1970, Hoshikawa et al. 1973, Nelson et al. 1972, Ballreich 1976). Results indicated that the increasing of maximal running velocity was obviously possible by higher step rate and shorter step length. This observation is supported by the duration of contact phases in relation to the flight times. The vertical oscillation of the center of gravity also decreased at higher velocities.

Mechanical power output increased parabolically with running velocity. The reasons for that were the increase of mechanical work done and shorter contact times. Work done during contact was 91-93 % of work during the total step cycle. The relative portion of positive work from the total work ranged from 57-61 % during a cycle period. The power values of positive work computed on the basis of total step cycle corresponded with earlier results (Fenn 1930b, Elftman 1940, Cavagna et al. 1964). This is also true with regard to the power values based on contact time (Fukunaga et al. 1978). During the contact period, however, the negative phase was much shorter than the positive phase and it remained always of the same portion (33-34 %) of the total work during contact. The ratio of powers in the negative and positive phases was 1. In further investigations this ratio should be studied using real segmental positive and negative force and work values. The absolute mechanical power value of the contact period was 3.5 - 3.2 times as high as the power from total step cycle. This means that the flight time in running is an important recovery phase for energy production especially in long distance running.

The horizontal and vertical forces of different body segments were never either positive or negative. Even the action of opposite arms was not symmetrical. Cavanagh et al. (1976) have suggested that the action of legs in running may be nonsymmetrical. However, the force produced for the center of gravity and for different segments in the phase of maximum force and, during the ground contact phase as force impulse, indicates the major segments and direction in force production. The horizontal maximal force of the total body mass center increased about four times at progressive velocities (40 % - 100 %). Most of this force was produced by the support leg. In this phase the swing leg decelerated. However, the horizontal impulse of the swing leg showed that this leg gave most of the increase of horizontal velocity during contact ($p < .001$). The velocity change of the heaviest segment, trunk and head, was small but in the phase of maximum force production it seemed to be second in the priority order. The horizontal force of arms in the phase of maximum force production and the horizontal impulses of arms were both negative.

On average the maximal vertical force of the total body increased 1.4 times as running velocity increased. The highest increase was in the force production of the support leg which was triple when running speed increased from jogging to maximal running velocity. The forces produced by arms and trunk were about constant and positive in the phase of maximum force. The vertical impulses of the above-mentioned segments showed that the role of arms and trunk was positive like the impulse of the support leg. The impulse of the swing leg in the vertical direction was negative. The roles in the horizontal and vertical directions were contrary. Although the maximal force in the vertical direction increased, the oscillation of the center of gravity decreased because of the shorter contact times with progressive running velocities. This was supported by the apparent spring constant values of the support leg, especially in the eccentric phase of the contact time.

The interpretation of the real meaning of the apparent spring constant has to be made with caution. This constant reflects the combined elasticity of the muscles, tendons and bones of the support leg. It is also expected that during contact the point value of the spring constant is changing continuously during contact because the length and tension of muscles and tendons (Frigo et al. 1978) of the support leg change in a very complex way.

Mechanical differences between running and walking are mainly found in the mechanism of recovery. The recovery of mechanical energy stored in stretched tendons and muscles occurs in running but a characteristic feature of walking is a pendulum motion in the recovery of mechanical energy (Cavagna et al. 1977). In earlier results it has been assumed that there is no energy exchange between or/and within body segments. Methods similar to the ones applied in this study have been used by Norman et al. (1976) in running and comparative values have been reported by Pierrynowski et al. (1980) in walking. In submaximal running the results are in agreement. In this work only maximal walking velocity has been used and in Pierrynowski et al. (1980) only submaximal velocity 1.54 ± 0.01 m/s with average step length of 0.79 ± 0.01 m. The total mechanical power output was then 6.9 W/kg. In velocities 3.2 ± 0.1 m/s in normal fast walking and 3.7 ± 0.2 m/s in race walking with step length 1.17 ± 0.02 m and 1.13 ± 0.03 m the total mechanical power output values were 7.5 ± 0.9 W/kg and 14.6 ± 2.9 W/kg, respectively. In both total walking styles the major part of power was coming from the changes of velocity in different body segments. In both cases least mechanical energy was used for lifting.

With respect to ground reaction forces during stance phase, Payne (1978) had measured normal and race walking in submaximal velocity (1.99 m/s, m = 60 kg) in normal walking and maximal velocity in race walking (4.69 m/s). In normal walking the resultant net force was 200 - 250 N and in race walking 620 - 670 N in planar movement.

In this study the mechanical power values in normal walking were about 51 % of the values in race walking. It was explained by higher ground reaction forces and slightly shorter stance phases in race walking. Horizontal impulses showed that there was a different pattern in the two types of walking because our "race walkers" were not skilled. Obviously mechanical efficiency was very low in this event. Horizontal impulses in race walking indicated that at the beginning of the stance phase the velocities of the support leg, trunk and arms were very low and were accelerating relatively more than in normal walking. The swing leg, on the contrary, had a fast horizontal speed at the beginning of the stance phase and was decelerating in the end of this phase.

In the film analysis of this thesis a seven segment model has been utilized in bisymmetrical vertical jump and a 13 segment model in other studies. The validation of the seven segment model has been carried out by comparing force-platform data with film analysis ground reaction forces derived from the free end of the segments. Maximum error in vertical maximal forces was 12 %. Pezzack and Norman (1979) have estimated corresponding error in the vertical direction to be 15 % and in horizontal forces 10 % using a six segment model in standing broad jump. The more links in the system used, the more error sources can be found. There is a great deal of deviation in the lengths of major segments especially in the trunk because of a relatively large range of shoulder movement. In addition, the axes of different joints are changing. Errors of this kind could be minimized by using different methods for smoothing the displacements and accelerations of the mass centers of segments. To enhance accuracy in force analysis the values of forces should be computed from the ground contact segment from force-platform data rather than calculating the values from free ended segments.

In spite of known error sources vertical jump studies showed that the major force producer for upward and maybe forward movement are knee extensors and the second most important force producer is ankle plantar flexion. In maximum performances the coordination of all body segments has to be right. Therefore, the timing of trunk, head and arms have to be well synchronized. The importance of these segments can vary but seems to be rather equal in vertical jumps performed from a fixed position. This fixed starting position revealed that at the beginning of different movements from a rest position the subjects performed naturally a very slight and, in human movement, very useful reaction movement in the opposite direction before the main action. In this movement the natural control system aimed to use muscle and tendon elasticity for better performance.

Normal and race walking represent activities in which elastic energy is not appreciably stored and utilized in the muscles (Cavagna et al. 1963, Asmussen and Bonde-Petersen 1974). This is most likely due to a more rolling type motion of the step over the heel (Basmajian 1976). Running at higher velocities (>5 m/s) and maximum running long jump take-off were performances in which both resultant force and power output were increased with an increase in speed of motion. A similar trend should be found in triple jump take-off for the first step.

However, during consecutive contacts in triple jumping, the maximal resultant forces are higher (2100 - 2300 N) with a decrease in speed of motion but power outputs lower (92 - 80 W/kg) because of longer contact times (0.127 - 0.195 s). The force-velocity and power-velocity curves change markedly when stored elastic energy and force produced in muscles is used. The increase of force and power output at higher velocities is most likely due to the eccentric contact phase, in which the active muscles are stretched (Cavagna et al. 1968, Bosco and Komi 1979). In physical performances at higher velocities the muscles are probably preprogrammed (Melvill-Jones 1971) to receive the impact, in which phase they are forced to stretch. In addition, it is known from hopping, jumping and running activities that the lower body extensor muscles are active slightly before first contact with the ground during the impact phase. In maximal running at higher velocities electrical activity in knee extensor muscles can be higher than in maximal isometric force production of the similar muscle group (Schmidtbleicher et al. 1978).

The pathway of the center of gravity during the take-off contact may demonstrate how well a jumper can tolerate high impact forces and consequently benefit from elastic energy and other force production. During non-specialist long jump take-off, consecutive contacts of steps and, in submaximal running, the center of gravity was considerably lowered during impact in all analyzed performances. Thus, it is suggested that the impact phase is an important part in all events performed at maximal velocities or run-up velocities. This must have a substantial influence on the concentric phase of contact and on final performance. A similar phenomenum in long jump had been hypothesized earlier by Bosco et al. (1976).

The apparent spring constant (Alexander and Vernon 1975) calculated for the eccentric and concentric phase indicated that for high power outputs in good performances the apparent spring constant values had to be very high in the eccentric phase. In this case the load on the support leg including muscles, tendons and bones has to be at least moderate and the vertical displacement of the center of gravity minimum. If man can tolerate the heavy load in the eccentric phase this may indicate that he is likely to be more successful in carrying out the concentric phase of the contact. In the concentric phase an optimum path of the center of gravity which is controlled by the human machinery mechanics should then be found.

The importance of a proper coupling of the eccentric and concentric phases for jumping and running performances can be examined from another point of view. Among the structural group of biomechanical principles there are two important mechanisms which contribute to attaining maximal velocity; the optimal path of acceleration and the coordination of different temporal impulses. Through the optimal path of acceleration it is possible to derive the optimal path of movement, eg. for the mass center ot the total body. The total output is always a relationship between the whole athlete and the task to do. In running, long jump take-offs and triple jumps, general principles from the construction and elasticity bases include maximal speed and minimal time during contact. Thus, depending on the goal of the sport event one has to use a suitable combination of step length and step rate at some actual velocity. This determines how maximal propulsion force can be obtained from the eccentric and concentric support phases in cyclic movements.

In order to know the optimal path of acceleration during contact phases in different events it is important to know, in physical terms, what the sources of acceleration are and what their relative contribution is. The movement of the center of gravity of man and the mass centers of different body segments are mostly curvilinear. Thus it can be assumed that the center of gravity of man is moving about a non-fixed imagined center of motion. According to a relative model of human movement (see Appendix, Figure 1) it may be possible that in horizontal movement man can have extra horizontal velocity by vertical force exerted during contact. A somewhat new perspective in the explanation of the acceleration path of the movement of the center of gravity would be to consider the center of gravity to be moving about the center of motion of a continually changing distance (radius of curvature, R) from the center of motion. Then the acceleration of the mass center in the contact phase is due to 1) acceleration influenced by the movement of center of motion, 2) acceleration influenced by the relative linear motion of the center of gravity and the center of motion, 3) coriolis acceleration influenced by the angular and linear velocity of the center of gravity about the center of motion and 4) acceleration due to the angular acceleration about the center of motion and the radius of curvature. An illustration of this causal acceleration behavior could be the individual performance of some athlete taking into account his physical characteristics like anthropometry and relative force production. This could make it possible to simulate and optimize all kinds of performances utilizing the biomechanical principle of coordination for maximal speed in minimal time.

In natural cyclic and jumping movement this theory could function as follows: the radius of curvature of the path of the mass center both in the eccentric and concentric phases reflects the mechanism of how the runner or jumper increases his total velocity after the lowest point during contact. In good performances the radius of curvature is longer in the eccentric phase than in the concentric phase (see Appendix, Figure 3). The shortening of the radius during the contact phase increases the angular velocity with respect to the apparent center of rotation of the movement. The higher the change of angular velocity, the higher will be the angular acceleration.

The tangential acceleration depends on the radius of curvature and angular acceleration in optimal combination. This tangential acceleration increases tangential velocity and, at the same time, the horizontal velocity especially when the radius of curvature changes from the infinite value to some small finite value before release. This may be one of the main advantages of the restitution of the elastic energy of the support leg and other body segments to increase both the vertical and horizontal velocity in different movements, especially at higher velocities.

The most important joints of man for walking, running and jumping are knee, ankle and hip joints. Rotational movement around joint axes is important for optimal energy transformation for all velocities (see Appendix, Figure 2). These axes are seldom fixed. Mostly these axes are changing so that the radius of curvature of different segments is also changing. With a complete extension of ankle, knee and hip man can reach a maximal benefit of acceleration for both the vertical and horizontal direction. Combined with the action of the support leg the coordination of other body segments, the swing leg and arms, can influence the radius of curvature and at the same time the path of the center of gravity.

From a mechanical point of view it can be concluded that mathematical modelling and simulation are important methods for finding out the optimal path of acceleration, coordination, mechanical energy output in different performances and, in cyclic movements, the individual step length - step rate ratio for optimal force propulsion during contact. For the optimal path of acceleration it is important to study, for further understanding, the meaning and mechanics of movement of the center of motion and the change in the radius of curvature about the center of motion. In addition, in the study of energy level in different movements the goal should be the optimal use of mechanical energy transformations from kinetic energy into rotational and potential energy. The opposite transformations are also important considering especially the transformation from rotational energy into kinetic energy level and the changes in the moment of inertia of the total body.

TIIVISTELMÄ

Tässä tutkimuksessa on pyritty 2-dimensionaalisen liikeanalyysin menetelmin selvittämään tavallisen ja kilpakävelyn, juoksun, pituushypyn ja kolmiloikan mekaniikkaa. Analyysimenetelmät eivät huomioineet kehonosien lateraalista ja segmenttien pituusakselin ympäri tapahtuvaa liikettä.

Tarkoituksena oli tarkemmin selvittää:

1. maksimaalisen tavallisen kävelyn ja kilpakävelyn, maksimaalisen ja submaksimaalisen juoksun, maksimaalisen pituushypyn ja kolmiloikan askelpituuden, -tiheyden ja vaakanopeuden välisiä riippuvuuksia ja syy-yhteyksiä,
2. mekaanisen energian eri muotoja ja mekaanisia tehoja tasaponnistuksessa ylöspäin, kävelyssä, juoksussa ja pituushypyssä,
3. kehonosien voimantuottoa ja voiman impulsseja tasaponnistuksessa ylöspäin, kävelyssä, juoksussa ja pituushypyssä sekä
4. tukijalan elastisuus-nopeus riippuvuutta juoksussa, pituushypyssä ja kolmiloikassa.

Koehenkilöinä oli 24 miesurheilijaa edustaen kansallista tai kansainvälistä tasoa eri urheilumuodoissa. Tasaponnistus ylöspäin, kävely, juoksu ja pituushyppysuoritukset tapahtuivat voimalevyanturin päältä, jolla taltioitiin magneettinauhalle reaktiovoimat. Suoritukset filmattiin samanaikaisesti kohtisuoraan sivulta kuvanopeuden ollessa 100-48 kuvaa sekunnissa. Suoritukset siirrettiin nivelpisteiden mukaan Vanguard-filmianalysaattorilla reikänauhalle ja edelleen tietokoneelle analysoitavaksi 7 tai 13 segmentin mallia Dempsterin mukaan soveltaen. Segmenttien liikkeet tasoitettiin 9:n asteen polynomisovitteen avulla.

Syklisten liikkeiden nopeutta arvioitiin askeltiheyden ja pituuden tulona. Kehonosittain tuotettua voimaa arvioitiin voimien riippumattomuuden mukaan mekaniikan toista peruslakia soveltaen. Voiman impulssi laskettiin voimalevyanturin voima-aikakäyrästä sekä voiman impulssin ja liikemäärän muutoksen vastaavuuden perusteella. Tehdyn työn ja edelleen tehon arviointi tapahtui mekaanisen energian (liike-, rotaatio-, potentiaali-

energia) muutoksia käyttäen. Tukijalan elastisuutta arvioitiin taas suorittajan painopisteen värähtelyyn perustuen.

Maksimaalinen juoksunopeus saavutettiin sekä askelpituutta että -tiheyttä lisäten. Edelliset muuttujat, nopeuden mukana lyhentyneet kontaktiajat sekä vähentynyt painopisteen pystyheilahdus mahdollistaisivat juoksunopeuden lisäämisen myös askeltiheyttä lisäämällä. Juoksussa mekaanisesta työstä tehtiin 91-93 % kontaktin aikana. Kaikilla juoksunopeuksilla eniten työtä tehtiin kehon osien painopisteiden nopeuksien muuttamiseksi. Positiivisen työn osuus vaihteli 57-61 % askelsykluksen ajalta. Kontaktin ajalta negatiivisen työn osuus oli 33-34 %. Positiivisen ja negatiivisen vaiheen tehojen suhde pysyi vakiona ($\approx$1). Tuleva tutkimus vaatii negatiivisen ja positiivisen työn erottamisen vaikuttavien negatiivisten ja positiivisten voimien mukaan segmenteittäin.

Juoksunopeuden kasvaessa hölkkävauhdista maksimiin koko kehoon vaikuttava vaakavoiman maksimi kasvoi nelinkertaiseksi. Pääosan tästä voimasta tuotti tukijalka. Heilahtava jalka oli tällöin hidastuvassa liikkeessä. Koko kontaktin aikana kuitenkin heilahtava jalka tuotti eniten vaakaimpulssia. Vartalon nopeus säilyi lähes vakiona. Vaakasuunnassa kädet olivat hidastavia kehonosia sekä maksimivoimiin että impulssiin perustuen. Koko kehon pystyvoima tuli 1,4 kertaiseksi juoksunopeuden kasvaessa 40 %:sta maksimiin. Suurin maksimivoimantuoton lisäys (3 kertainen) oli tukijalalle. Voiman maksimivaiheen aikana vartalon ja käsien voimat olivat positiivisia ja likimain vakioita. Viimeksi mainittujen segmenttien ja tukijalan impulssit osoittivat niiden liikkeiden olevan kokonaisuudessaan nopeutta lisääviä kun taas heilahtava jalka oli hidastava. Vaikka ylöspäin suuntautuva voima lisääntyi, väheni painopisteen pystyheilahtelu, koska voiman vaikutusaika lyheni. Tätä havaintoa tukivat myös tukijalan jousivakion arvot varsinkin kontaktin eksentrisestä vaiheesta.

Mekaaniset erot kävelyn ja juoksun välillä ovat askellustavassa, jolloin mekaanisen energian hyväksikäyttö on erilaista. Kävelyssä energia siirretään etupäässä segmenttien heilahdusliikkeisiin perustuen. Juoksussa taas energian siirto tapahtuu lähinnä jännitettyjen venyvien lihasten ja jänteiden välityksellä. Normaalin ja kilpakävelyn eroja tällä tutkimuksella ei yleistäen voinut selvittää, koska kilpakävely suorituksena oli liian outo tämän tutkimuksen koehenkilöille.

Kaikissa maksimaalisissa suorituksissa erityisesti hypyissä vaikuttavat lopulliseen tulokseen tahdonalainen ja refleksinomainen hermo-lihastoiminta ajoituksen ja voiman tuoton puolelta, lihasten histokemiallinen rakenne, lihasten voimapituusominaisuudet, nivelkulmat sekä lihasten, jänteiden ja luiden kimmo-ominaisuudet. Toiminnallisesti näyttäisi siltä, että polvien ojentajien voimantuotto koko kehon painopisteelle olisi tärkein. Toisena tärkeysjärjestyksessä olisi nilkkojen ojentajien ja kolmantena vartalon ojentajien toiminta. Täydellisesti onnistuneen maksimisuorituksen eli unelmasuorituksen todennäköisyys käytännössä on pieni, koska suoritukseen vaikuttavia tekijöitä on paljon. Vauhdillisissa hypyissä näyttää jo törmäysvaiheen 1. eksentrisen vaiheen painopisteen rata ennustavan hypyn onnistumisesta. Parhaissa hypyissä suorittajan tukijalan voiman välitysmekanismin on siedettävä suurempia voimia kuin huonoissa hypyissä, ettei painopiste laskisi liian paljon. Tämä edellyttää sopivaa esi-ohjelmoitua jännitystä suorituksen aikana venyvissä lihaksissa ja jänteissä, joiden kautta liike-energian suuntaus hyppyä varten tapahtuu sopivalla tavalla. Tukijalan jousivakion korkeat arvot tukevat kuvailtua mekanismia nimenomaan hyvien suoritusten eksentrisistä vaiheista.

Biomekaniikan periaatteiden kannalta maksimisuorituksissa toimii kaksi tärkeää mekanismia maksiminopeuden saavuttamiseksi kontaktin aikana. Tällöin suorittajan painopisteen kiihtyvyyden radan ja kehonosittain tuotettujen impulssien tulisi olla ajallisesti optimaalisia. Riippuen suorituksesta on vielä löydettävä optimaalinen askeltiheyden ja -pituuden suhde suorituksessa käytettyyn vauhtiin nähden. Tämä määrännee, miten kontaktin aikana voidaan tuottaa maksimaalinen eteenpäin vievä voima siirryttäessä eksentrisestä vaiheesta konsentriseen vaiheeseen.

Etsittäessä optimaalista kiihtyvyyttä eri suorituksia varten kontaktin ajalle on tärkeä tietää, mitkä ovat fysikaalisesti kiihtyvyyttä tuottavia tekijöitä. Ihmisen painopisteen liike voidaan kuvitella tapahtuvaksi kaarevaa rataa pitkin liikkuvan liikekeskuksen suhteen. Tämän suhteellisen mallin mukaan kokonaiskiihtyvyys riippuu 1) liikekeskuksen lineaarisesta liikkeestä, 2) suorittajan painopisteen ja liikekeskuksen suhteellisesta lineaarisesta liikkeestä, 3) coriolis-kiihtyvyydestä, joka aiheutuu painopisteen suhteellisesta lineaarisesta nopeudesta ja kulmanopeudesta liikekeskuksen suhteen sekä 4) liikkeen kaarevuussäteestä ja painopisteen kulmakiihtyvyydestä liikekeskuksen suhteen. Mallin mukainen ajattelu mahdollistaa erilaisten suoritusten painopisteen kiihtyvyyden radan optimoinnin maksiminopeuden saavuttamiseksi rajoitetussa ajassa. Samalla selviäisi, mikä on mainittujen kiihtyvyyslähteiden osuus kokonaiskiihtyvyydestä.

Esitetty teoria toiminee juoksuissa ja vauhdillisissa hypyissä seuraavasti: hyvissä suorituksissa painopisteen kaarevuussäde on eksentrisessä vaiheessa pitempi kuin konsentrisessa vaiheessa. Kaarevuussäteen lyheneminen kontaktin aikana suurentaa kulmanopeutta liikekeskuksen suhteen. Kulmanopeuden kasvaessa kasvaa myös kulmakiihtyvyys tai pysyy positiivisena. Tangentiaalinen kiihtyvyys taas riippuu kaarevuussäteen ja kulmakiihtyvyyden tulosta. Kulmamuutoksista aiheutuva kiihtyvyys voi lisääntyä myös coriolis-kiihtyvyyden vaikutuksesta. Positiivinen tangentiaalinen kiihtyvyys lisää tangentiaalista nopeutta ja samalla horisontaalinopeutta. Koska painopisteen liike johtuu osittain ehkä suureltakin osalta tukirakennelmien elastisesta toiminnasta, tämä voi olla päämekanismi elastisen energian hyväksi käytössä muutettaessa eri energiamuotoja segmenteittäin liike-energiaksi.

Kävelyssä, juoksussa ja hypyissä keskeisimmät nivelet ovat polvi, nilkka ja lonkka. Pyörimisliikkeet mainittujen nivelakselien ympäri ovat keskeisiä optimaalisen energian siirron kannalta. Nivelakselit nivelessä ovat muuttuvia akseleita, jolloin myös segmenttien painopisteet ovat kaarevassa liikkeessä, jonka kaarevuussäde muuttuu alituisesti. Täydellisessä nilkan, polven ja lantion ojennuksessa lienee mahdollista kiihtyvyyden kannalta saada suurin hyöty sekä horisontaali- että vertikaalisuuntaan. Yhdistäen tukijalan, heilahtavan jalan, vartalon ja käsien toiminnan on myös mahdollista vaikuttaa kaarevuussäteeseen ja samalla kehon painopisteen liikkeeseen.

Yhteenvetona mekaanisen suorituksen kannalta matemaattisten mallien rakentaminen ja simulointi ovat tärkeitä vaiheita etsittäessä eri suorituksiin optimaalista kiihtyvyysrataa, koordinaatiota, mekaanista tehoa, yksilöllistä askelpituus-tiheyssuhdetta sekä voimantuottoa. Tulevaisuudessa tulisi entistä enemmän pyrkiä selvittämään kaarevissa liikkeissä kaarevuussäteen ja kulmamuuttujien merkitystä optimaaliselle kiihtyvyysradalle rajoitetussa ajassa sekä liike-energian muuttumista rotaatio- ja/tai potentiaalienergiaksi. Vastaavia energian muutoksia on selvitettävä myös päinvastoin tapahtuvina ja suhteutettuna sekä liikkuvaan massaan että liikkeen aikana muuttuvaan koko kehon hitausmomenttiin varsinkin pyörimisliikkeiden ollessa kyseessä.

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APPENDIX

1. A relative model of human movement

The purpose of this appendix is to describe the relationships between different factors influencing velocity during human movement.

The movement of the center of gravity of man and the mass center of body segments is mostly curvilinear. Thus it can be assumed that his movement has a moving, imagined center of motion (CM). The causal movement study has to take into consideration both the movement of the center of gravity and the center of motion at the same time and their relationship (Plagenhoef 1968, Miller and Nelson 1973).

This relative model of human movement can be explained using the accelerations during contact in cyclic motion. Let Σ_O be a fixed planar coordinate system and Σ the planar coordinate system of the center of motion (Figure 1). Thus the radius of curvature R can be derived from formula

$$\frac{1}{R} = \frac{d\alpha}{ds}$$

where $d\alpha \approx \frac{dy}{dx}$

or $\tan d\alpha = \frac{dy}{dx}$

and $ds = \sqrt{dx^2 + dy^2}$ (Myrberg 1967).

If the radius vector of the center of gravity is $\bar{r}_O$, $\bar{r}$ is the radius vector of the center of motion and $\bar{R}$ the radius vector from the center of motion to the center of gravity

then $\bar{r}_O = \bar{r} + \bar{R}$.

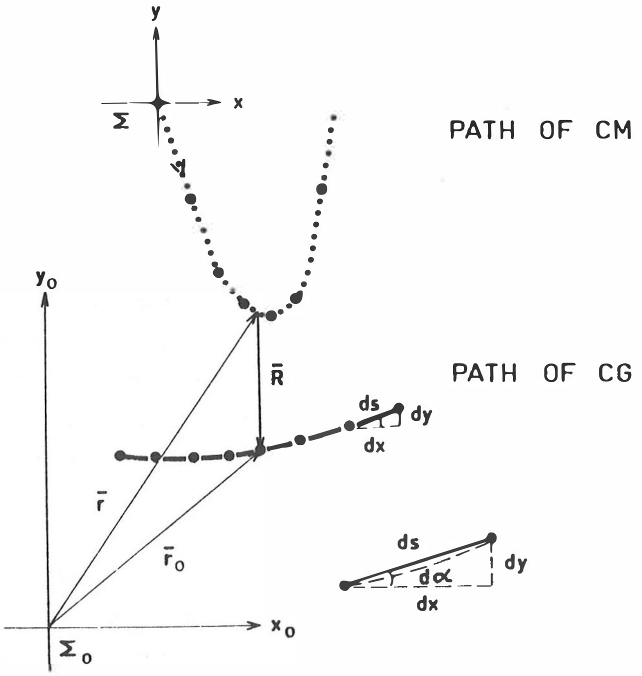

Figure 1. The relative motion of the center of gravity (CG) about the center of motion (CM). The symbols are explained in the text.

The coordinates of the center of motion (x, y) can be calculated as follows:

$$\begin{cases} x = x_o - R\sin\theta \\ y = y_o + R\cos\theta \end{cases}$$ (Lindelöf 1928)

where x_o = x-coordinate of the center of gravity,
y_o = y-coordinate of the center of gravity, and
$\theta \approx d\alpha$

If the motions occur at the same time in both coordinate systems so that the fixed coordinate system Σ_o does not move and

Σ moves but does not rotate, then the center of gravity of man can rotate about the coordinate system Σ. If this rotation is taken into consideration, the formula of acceleration of the center of gravity can be written as follows:

$$\ddot{r}_o = \ddot{r} + \ddot{\bar{R}} + 2\,(\bar{\omega} \times \bar{v}) + \dot{\bar{\omega}} \times \bar{R} \qquad \text{(Stenman 1967)}$$

where $\ddot{r}$ = acceleration influenced by the movement of the center of motion,

$\ddot{R}$ = acceleration influenced by the relative linear motion of the center of gravity and the center of motion,

$2(\bar{\omega} \times \bar{v})$ = coriolis-acceleration, and

$\dot{\bar{\omega}} \times \bar{R}$ = acceleration due to the angular acceleration about the center of motion and the radius of curvature.

Using formula we can calculate the change of velocity during contact in different performances such as walking, running, vertical jump, long jump and triple jump. It also gives the possibility of simulating and optimizing different performances in order to lose or gain some velocity during the contact period. Anyway, the presented formula shows that in horizontal motion additional horizontal velocity can ve gained by jumping upwards. This can be due to the change of radius of the curvature, angular velocity and acceleration about the center of motion.

2. Applications of the relative model of human movement

The most important joints for walking, running and jumping are the knee, ankle and hip joints. In these joints the center of motion changes during the total range of joint movement (Smidt 1973, Bojsen-Möller 1978). Additionally, the toe contact point and its distance from the center of gravity of the foot is changing continuously. Figure 2 presents the path of the center of motion in the knee joint. This figure shows that the radius of curvature for the center of gravity of the thigh will be maximum when the knee joint is in extension. A similar phenomenon can be seen in the extension of the hip, in the plantar flexion of ankle and from the contact point to the center of gravity of the foot.

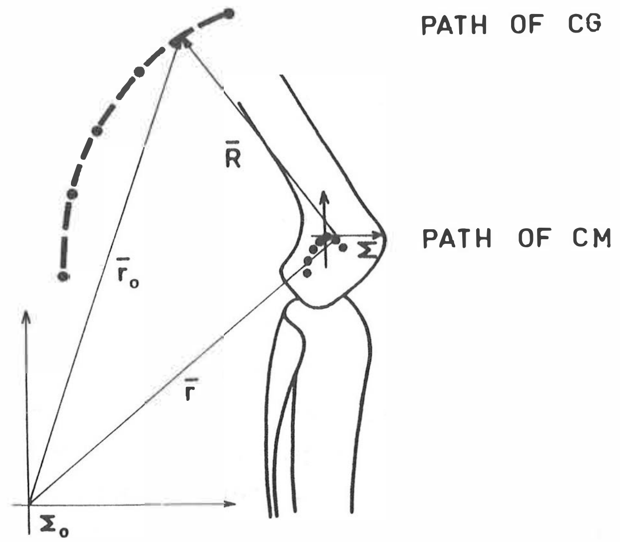

Figure 2. The relative motion of the thigh about the center of motion in the knee joint according to Smidt (1973).

In addition, the instantaneous positions of arms and the swing leg can move the radius of curvature upwards from the hip joint. Suitable utilization of arms in the vertical direction could be beneficial for horizontal acceleration and velocity.

Figure 3 presents a fictitious drawing of two different cyclic motions during the contact phase. It can be assumed that total velocity in the impact phase is the same. The more the center of gravity is going downwards during the contact, the more the path of the center of motion is decelerating horizontal velocity due to the pure motion of the center of motion and the short radius of curvature. According to conditions presented in Figure 3 it seems to be impossible to reach the same horizontal release velocity using those different paths of the centers of gravity.

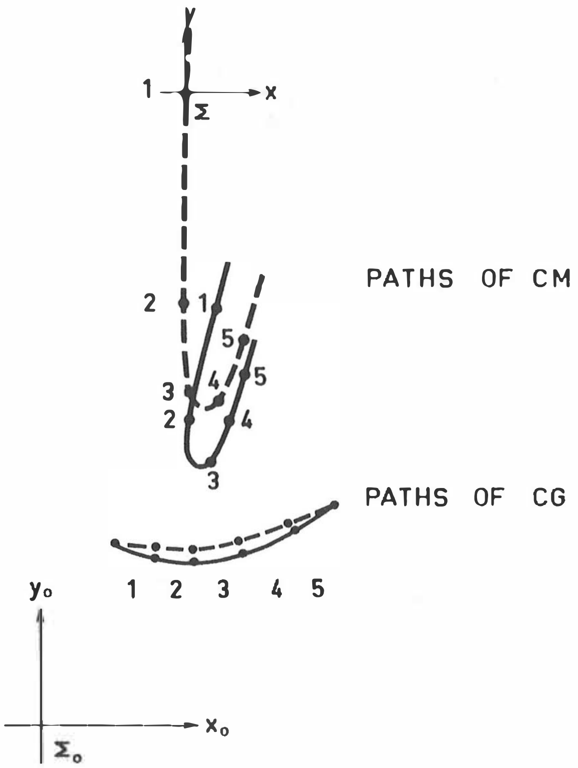

Figure 3. Fictitious drawings of two different cyclic motions during the contact phase.

It might be possible to construct a model involving a greater number of combined centers of gravity and centers of motion. Figure 4 shows drawings with two combined centers of gravity and motion. This relative model could be a suitable and causal model for different throwing events and pole valuting.

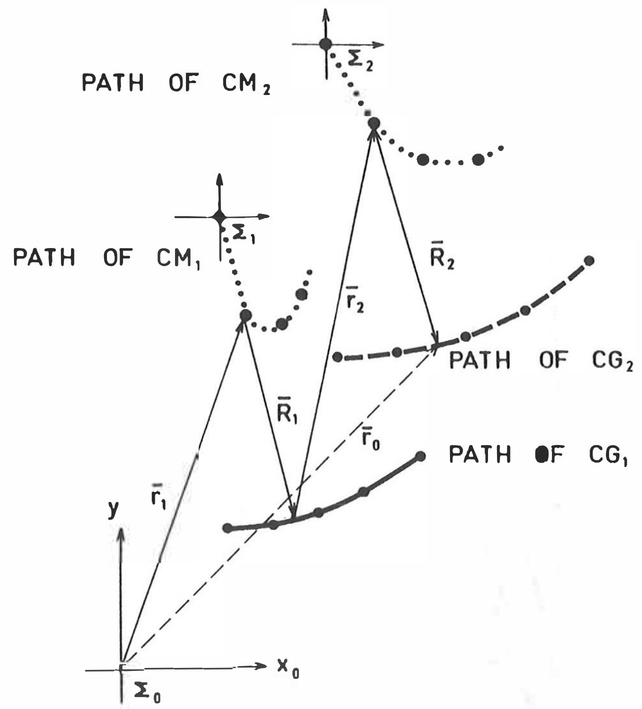

Figure 4. The relative motion of two different coupled centers of motion in order to get high velocity for the center of gravity of mass two (CG_2).