WORK-ENERGY ANALYSIS OF ICE SKATERS UNDER PROGRESSIVE CONDITIONS OF FATIGUE

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INTRODUCTION

The biomechanical manifestations of fatigue in the hockey skating stride have thus far been documented by Marino and Potvin (1989) on a gross mechanical level . Their results show that decreases in skating velocity are due to slower rates of movements caused by changes in skating mechanics.

Specifically, decreased moments of force and decreased power output at the knee , and decreased maximum energy output at the thigh and the lower leg were attributable to the decrements in the skating mechanics.

This study further clarifies changes occurring with fatigue by identifying energy deterioration in specific segments as well as variations in the ability to passively exchange energies both within and between segments. This segment by segment mechanical energy analysis has been used often in gait analyses (Cavagna,Saibene & Margaria, 1963 , Pierrynowski , Winter and Norman , 1980), running analyses (Cavagna, Saibene & Margaria 1964 , Williams & Cavanagh, 1983), and more recently in the analysis of cross country skiing (Norman, Caldwell & Komi 1985). Results yield mechanical efficiency values for the movement patterns and thus give a basis for improving segmental mechanics.

METHODS

Nine highly skilled hockey players aged seventeen to twenty-one served as the subject pool for this experiment. They were asked to skate twelve 20 m lengths at maximum speed with an intervening stop and start between lengths. All players had visible joint markings and were filmed for each of the second, tenth and twelfth length of skating.

A Locam camera operating at 100 frames per second was set up perpendicular to the skating path near one end of the ice. Each player was filmed for two full skating strides so that coordinate data could be recorded for a full stride (from push off of one foot to push off of other foot).

The film was digitized using an Altek AC30 digitizer interfaced with an Apple II microcomputer. A 13-member linked segment model (trunk, upper arms, forearms, hands, thighs, lower legs) was constructed from the x, y, coordinate data of the segmental endpoints. The coordinate data were smoothed using a Butterworth fourth order low pass digital filter with a cutoff frequency of 10 Hz.

The Pierrynowski (1980) method was used to determine energy transference values (work done by the body) and the rate of energy exchange (mechanical power). A general linear model statistical program generated by SAS was used to do one-way repeated measures ANOVAs and a Tukey post-hoc test for energy transference means comparison and for individual segments means comparison.

The underlying assumption of this method is that the energy of the centre of mass of the body will equal the sum total of all individual segmental energies. The work required to move any segment of the body is arrived at by summing the absolute energy changes occurring in that segment of the body. The energy in a particular segment at any one time can be calculated by summing the potential energy and the kinetic energies due to translation and rotation:

$$E = mgh + 1/2mv^2 + 1/2\ IW^2$$

where E = total energy of the segment
m = the mass of the segment
v = translational velocity of the segment relative to the ice

h = vertical position of the segment relative to the ice
I = segmental moment of inertia
W = absolute angular velocity of the segment

Calculating segmental energies over a number of frames of film will allow calculation of absolute energy changes for that segment over time. The next logical step is to sum all individual segmental energy changes over time to arrive at an internal mechanical work value for the whole body. The equation for Wwb which accounts for energy transfer within and between segments is as follows:

Wwb = sumE segi + sumE segi+1 +....+ sumE segn

where sumE seg = the sum of all energy changes for a given segment throughout all frames of film.

To calculate the amount of work done by the body assuming energy transfers only within but not between segments all of the individual segmental energies are summed over time and the resulting sum of the absolute energy changes will yield Ww:

Ww = sumE

where sumE = the change in the total sum of all segmental energies taken from one frame to the next.

The amount of work done assuming no energy transfers within or between segments (Wn) is calculated by summing absolute changes for each E component for each segment, then summing these totals for all segments for all frames of film.

Wn for one segment = : EP: + : EK: + : RE:

where EP = change in potential energy from one frame to the next
EK = change in kinetic energy from one frame to the next
RE = change in rotational energy from frame to frame

Having found Wn, Wwb and Ww, it is finally possible to calculate the magnitudes of energy transfers within and between segments (Twb), between segments (Tb) and within all segments (Tw) as follows:

Twb = Wn - Wwb
Tb = Ww - Wwb
Tw = Twb - Tb

RESULTS

No statistically significant differences were found between the three skating trials for either energy transference or work done by the body. However, all work rate and rate of energy exchange values (except for work rate done by the body assuming energy exchange within and between segments - RWWB) had significant F-ratios at $p < 0.05$. The post-hoc analysis with alpha < 0.05 revealed that differences for the dependent variables occurred between the second trial and the tenth trial and between the second trial and the twelfth trial (except for the rate of energy exchange within the segments of the body - RTW). No significant differences occurred between the tenth and twelfth skating trials.

The data summarizing the results of the study are listed in the tables that follow. Tables 1 and 2 present the absolute work and energy transfer values respectively, while Tables 3 and 4 summarize the work and energy exchange rates.

TABLE 1
Absolute Work Values
(N = 9)

		Trial		
		2	10	12
Wn	X	2000.8 J	1818.3 J	2163.7 J
	S	409.7	494.6	592.8
Wv	X	1787.2	1615.7	1897.3
	S	407.5	483.8	611,3
Wvb	X	610.3	763.4	888.7
	S	289.2	270.8	318.0

TABLE 2
Energy Transfer Values
(N = 9)

		Trial		
		2	10	12
Tv	X	207.7 J	211.4 J	265.6 J
	S	49.9	50.7	92.4
Tb	X	1174.1	852.7	1009.3
	S	299.1	210.4	278.4
Twb	X	1381.5	1064.3	1274.9
	S	306.4	247.6	274.8

TABLE 3
Work Rates
(N = 9)

		Trial		
		2	10	12
RWvb*	X	1444.8 W	1051.1 W	1238.8 W
	S	394.0	417.5	462.7
RWv*	X	3885.7	2316.3	2692.4
	S	885.8	552.3	689.2
RWn*	X	4337.1	2634.5	3059.6
	S	892.4	578.9	650.5

* Statistically significant differences between trials at $p < 0.05$.

TABLE 4
Energy Transfer Rates
(N = 9)

		Trial		
		2	10	12
RTv*	$\bar{X}$	451.2 W	318.2 W	363.7 W
	S	78.3	56.7	69.4
RTb*	$\bar{X}$	2572.2	1265.2	1453.6
	S	662.1	430.1	481.9
RTvb*	$\bar{X}$	3023.4	1265.2	1817.3
	S	679.4	387.6	402.5

* Statistically significant differences between trials at $p < 0.05$.

Individual segment analysis on total energy values revealed significant F-Ratios at $p < 0.05$ for all segments throughout the three trials. The post-hoc test with $p < 0.05$ revealed that the trunk, thigh, hand, arm and forearm had significantly different total energy values between the second and tenth trials. The trunk, thigh, hand, leg and foot were significantly different between the tenth and twelfth trials. The trunk, leg, foot, arm and forearm were significantly different between the second and twelfth trials.

DISCUSSION

The rate at which the body can passively exchange energy within and between segments descreased significantly between the second and tenth of the ice skating task, but there was no significant decrement in the rate of energy exchange between the tenth and twelfth length.

Between the second and the tenth trial, the arms and forearms show significant decreases in total energy. No further decrements were evidenced between the tenth and twelfth trials. The arms could be used initially to transfer energy between segments and then upon the onset of fatigue, fail to effectively transfer momentum to the body, thereby contributing to the decreased rate at which the whole body is able to exchange energy. The thighs and the trunk being larger segments, however, would, be a greater influence on the rate of total body energy transference.

As the skater progressed to the tenth trial of the task, total energy of the trunk and thighs decreased. Marino & Potvin (1989) showed that stride length is not affected by the onset of fatigue, and this would explain why none of the work values were significantly different. The contribution of the thigh and trunk to significantly decrease the rate of energy exchange hinges on the ability to utilize gravity. The passive motion of the recovering leg allows the thigh (and subsequently the knee and foot) to attain an optimal height above the ice at the end of the swing phase. But because of the decreased moment of force and power output at the knee occurring during fatigued skating (Marino & Potvin, 1989), there is a decreased ability to convert potential energy (EP) due to height of leg above the ice to translational kinetic energy (EK), thus decreasing the translational velocity of the body.

From the tenth length to the twelfth length there was no significant decrease in the body's rate of energy exchange, yet the thigh, trunk, leg and foot exibited significant decreases in total energy. The leg and foot are used to maintain stride length and not recovery height of the free leg. This decreases the attainable height of the thigh during recovery and subsequently EP at the end of the swing phase for the thigh, leg and foot. This translates to less power per push. There are no significant decreases in skating velocity or stride rates from the tenth to twelfth trials (Marino & Potvin, 1989) nor are there further decreases in the rate of energy exchange. Decreases in the ability of individual segments to passively transfer energy may be associated with metabolic costs.

CONCLUSIONS

This segmental energy analysis of the hockey skating stride provided a segment by segment assessment of how energy flow is affected by fatigue as well as the proficiency of the segments to passively exchange energy within and between segments. Significant decreases in the rate at which the body could transfer energy occurred between the second and tenth skating trial length. During this time, marked decreases in total energy were observed in the thigh and trunk segments.

Being able to pinpoint where significant decrements in energy transference occur, both within and between segments, over some period of time, enables the observer to retire a skating subject before a more substantial deterioration in skating performance occurs. A further study could more finely partition the length trials to further clarify exactly where the rate of energy exchange deteriorates.

Based on the results of this study and with the limitations in mind, several conclusions are warranted. There are no significant differences in absolute work done or energy transferred during skating under varying levels of fatigue. There are, however, significant decreases in both work rates and energy transfer rates as a skater progresses from a non-fatigued condition.

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