QUANTITATIVE ANALYSIS OF HIGH JUMP STYLES

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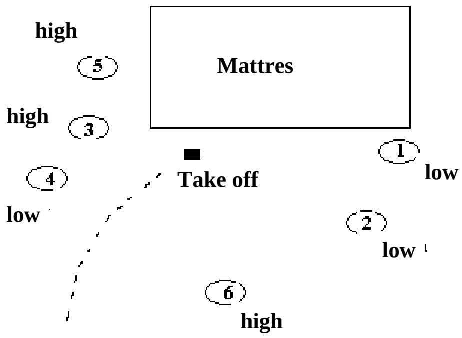
The purpose of this study is to investigate the relationship between the kinematics and the dynamics in the elite high jumpers. The analysis was based on an accurate anthropometrical model of the body and on the kinematics data obtained through optical motion capture in an indoor training session. The measure of the angular momentum has given suggestions on how to improve the efficiency of the gesture. The analysis of the kinematics coordination and of the inter-trial variability suggest that athletes should focus more either on the kinematics or on the dynamics. From these data, the angular momentum and the kinematics variability do not appear to be correlated.

KEY WORDS: high jump, 3D motion capture, kinematics, modelling.

INTRODUCTION: High jump can be described as the combination of a twist and a backwards summersault, which have to be executed in a coordinated manner while translating in a direction perpendicular to the bar (Dapena, 2002). To achieve a successful task, the athlete should acquire an adequate amount of angular momentum in the take off phase, in both the vertical direction and in a transversal direction parallel to the bar. The requirements for a successful jump have been studied both theoretically and experimentally mainly by Dapena (Dapena 1995a, 1995b, 1997; see also Iboshi et al., 1997; Liu et al., 1998, http://www.ciachr.org/hj.htm). In these studies the effect of different styles on the gesture are described. However, we did not find any reports on the motion variability, which is interesting to get insights on the strategy used to control the gesture. This is the main topic of the present paper. Besides this, the contribution to the angular momentum obtained by the limbs is reported and discussed.

METHOD:

(a)



(b)

Figure 1. The training set-up in shown in panel (a). Six cameras were positioned around the runaway according to the schema in panel (b). The cameras positioned at about 50cm from the ground are indicated with *low*, while the cameras positioned at > 2m from the ground with *high*.

Three international level women high jumpers (highest jump between 1.86 and 1.89m), AA., GG. and EE were filmed during an indoor camp training session. Their motion was recorded using an optoelectronic motion capture system (SMART3D^{TM}, BTS, Milan, Italy) with 6 infrared cameras (frame rate 120 Hz). The calibrated volume was approximately 6m x 3m x 2.5m (Figure 1a), the reference frame was set with the *z* axis vertical and the *x* axis parallel to the bar. Cameras were carefully positioned such as to survey the maximum number of markers; a few jumps were recorded to analyze the coverage degree of each camera. The final position of the cameras is shown in Figure 1b. Particular care has been put in designing adequate markers. In fact, the markers provided by the producer did not satisfy our needs:

as they were constituted of plastic spheres at the top of rigid supports, thus, they could produce harm to the athletes when landing over the mattress. Therefore we developed specially designed soft markers. First we tried a retro-reflective net of different shapes and dimensions (Figure 2a). As the power of the reflected light was not enough to get a clear marker image, we developed a different marker, shown in Figure 2b. This is constituted of a soft support (foam), roughly spherical, covered with retro-reflective cloth by 3M (3M, St. Paul, MN, USA). This guarantees both retro-reflective power and marker softness. All markers were then sewed to a rectangular piece of cloth of 10 x 10mm. The quantitative analysis of the motion was carried out under the assumption of chain of rigid bodies. The body was subdivided into 16 segments: head, hands (2), forearms (2), arms (2), upper and lower trunk, abdomen, thighs (2), lower legs (2) and foots (2). The anthropometric parameters; moment arms, moments of inertia, center of mass, were derived for each segment from the work of de Leva (1996). The position of the segments extremities was computed from the 3D markers' positions produced by the motion capture. Markers were positioned on the athletes as in Figure 2C and they were arranged as in Figure 2D. From the anthropometric data and the kinematics data, the angular momentum of the body was computed with respect to the center of mass of the entire body following Dapena (1995a, b). We verified a-posteriori the adequacy of the model checking that the three components of the angular momentum were constant after take off.

(a) **(b)** **(c)** **(d)**

Figure 2. Panel (a): the first prototype of soft markers constituted of a retro-reflective net. Panel (b): the marker developed for the experiments. It is constituted of a deformable support (foam), roughly spherical, covered with a retro-reflective cloth by 3M. Panel (c): the markers positioned on an athlete. Markers of the trunk and abdomen are attached on the back such as they are visible from downwards (lower cameras in Figure 1b) also when the athlete twists to overcome the bar. Markers on the limbs are attached with an elastic band. Panel (d): the arrangement of the markers is sketched. Notice marker MK12, which is used to compute twist of the upper trunk with respect to the lower trunk and the markers over the wand on the athlete's head used to determine head motion.

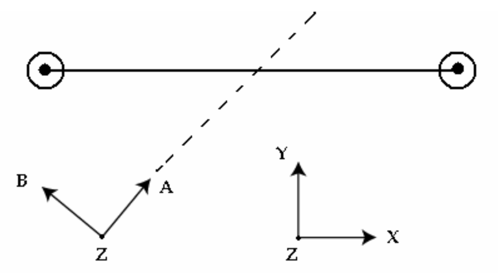
RESULTS: As it is clear from Fig. 3, the three athletes used different styles and this is associated to different angular momentum values (Table 1). We have studied the contribution of the limbs to the total momentum. For EE the entire longitudinal momentum, (Mz, twist) is produced through the motion of the leading leg (Mz-LeadLeg) which follows an arched trajectory with significant leg abduction. The momentum produced by the lower limbs is reduced by the motion of the arms, which are lifted symmetrically and produce an opposite momentum (Mz-Arms). The leading leg for AA and GG also follows an arch, but with little abduction. As a result, Mz obtained by the leading leg is smaller and it has to be integrated by a trunk twist. EE seems to have no trunk twist at take off. AA and GG exhibit an asymmetrical motion of the arms which produces little longitudinal momentum: GG motion is slightly more efficient in obtaining a higher Mz. The horizontal components of the momentum (Mx and My) are measured in two reference frames: (x,y) referred to the bar and (l, f) referred to the body orientation at take off (Table I). The analysis of Mx and My shows that the axis of transverse momentum (summersault) for AA and GG has an angle of few degrees with respect to the bar; this allows a relative motion of the body segments, and in particular of the arms to increase twist through catting (Dapena, 1995a). EE, on the contrary, has a transverse momentum already aligned with the bar at take off and this justifies the lack of a twist momentum. This may be due to the small value of Mf which is penalized by the large negative value of the forward momentum produced by the leading leg. These results suggest that EE may get a better momentum by changing the motion of the leading leg and of the arms in the take off phase.

EE	Mz	Mz-Arms	Mz-LeadLeg	Mx	My	Ml	Mf	Ms (abs)	Mf-Arms	Mf-LeadLeg
Jump 03	-29	20	-49	-99	-8	-84	53	100	53	-70
Jump 04	-31	21	-52	-92	-8	-79	49	93	43	-69
Jump 06	-40	9	-44	-94	-5	-76	55	94	42	-58
Jump 07	-38	15	-46	-94	-6	-76	56	95	47	-67
Jump 08	-36	16	-48	-95	-4	-77	57	95	51	-70
Jump 09	-37	11	-49	-102	-6	-84	57	102	57	-71
Jump 10	-35	15	-44	-84	-2	-68	49	84	51	-69
Jump 11	-38	12	-46	-87	-12	-72	50	88	54	-73
Jump 12	-43	13	-48	-97	-4	-75	61	97	46	-61
Jump 13	-39	10	-45	-89	-2	-71	53	89	56	-65
Jump 14	-38	14	-43	-90	1	-65	62	90	59	-67

AA	Mz	Mz-Arms	Mz-LeadLeg	Mx	My	Ml	Mf	Ms (abs)	Mf-Arms	Mf-LeadLeg
Jump 01	-49	8	-27	-130	22	-95	91	132	63	-59
Jump 02	-49	6	-24	-120	28	-79	94	123	57	-52
Jump 03	-56	5	-22	-136	30	-95	101	139	56	-52
Jump 04	-57	2	-22	-139	19	-103	94	140	65	-62
Jump 05	-71	8	-26	-166	37	-115	125	170	64	-58
Jump 06	-70	4	-26	-125	3	-100	75	125	55	-70
Jump 07	-74	9	-24	-144	17	-108	96	145	70	-63
Jump 09	-70	4	-22	-141	29	-104	99	144	67	-63
Jump 10	-68	10	-29	-139	25	-104	95	141	60	-64
Jump 11	-69	10	-29	-145	28	-106	102	147	60	-63
Jump 12	-61	10	-27	-124	19	-92	86	126	59	-62
Jump 13	-69	12	-29	-136	19	-106	88	138	61	-65

GG	Mz	Mz-Arms	Mz-LeadLeg	Mx	My	Ml	Mf	Ms (abs)	Mf-Arms	Mf-LeadLeg
Jump 01	-70	-9	-22	-149	35	-84	127	153	52	-27
Jump 02	-73	-12	-25	-144	21	-89	115	145	56	-30
Jump 03	-70	-14	-25	-147	26	-89	120	149	57	-27
Jump 06	-74	-16	-25	-153	18	-90	125	154	62	-32
Jump 07	-64	-7	-24	-156	47	-81	141	163	58	-22
Jump 08	-67	-10	-31	-137	52	-65	132	147	64	-35
Jump 09	-76	-14	-32	-160	18	-106	121	161	56	-45
Jump 11	-64	-10	-28	-154	41	-83	136	159	61	-24
Jump 12	-75	-9	-28	-141	27	-76	122	143	56	-32
Jump 13	-68	-9	-25	-147	48	-74	135	154	57	-26

$$\vec{M}s = \vec{M}f + \vec{M}l$$



Athlete:EE		
Joint 1	Joint 2	C
l shoulder	r shoulder	0,91
r ankle	r shoulder	-0,87
l ankle	r shoulder	0,82
r thigh	r elbow	-0,79
r knee	r elbow	-0,82
l thigh	r elbow	0,84
r hip	r wrist	-0,81
r ankle	r wrist	0,78
l hip	r wrist	0,81
l elbow	l shoulder	0,81
r ankle	l shoulder	-0,76
l ankle	l shoulder	0,86
l thigh	l elbow	0,8
l ankle	l elbow	0,8
r ankle	r hip	-0,77
l hip	r hip	1
l thigh	r thigh	-0,85
l hip	r ankle	-0,77

Athlete:AA		
Joint 1	Joint 2	C
r hip	r shoulder	0,85
r thigh	r shoulder	-0,94
l hip	r shoulder	0,85
l thigh	r shoulder	0,94
l elbow	l shoulder	-0,95
r thigh	r hip	-0,92
r knee	r hip	-0,94
r ankle	r hip	-0,85
l hip	r hip	1
l ankle	r hip	0,92
r knee	r thigh	0,92
l hip	r thigh	-0,92
l thigh	r thigh	-0,94
l ankle	r thigh	-0,93
r ankle	r knee	0,9
l hip	r knee	-0,94
l ankle	r knee	-0,96
l hip	r ankle	-0,85
l knee	r ankle	0,88
l ankle	r ankle	-0,87
l ankle	l hip	0,92

Athlete:GG		
Joint 1	Joint 2	C
r knee	r elbow	-0,78
l elbow	l shoulder	-0,81
l hip	r hip	1
l knee	r ankle	0,92

Table 1. The momentum components of the successfull jumps, computed at take off, are reported in the left column. Sign conventions are depicted in the bottom figure for two reference systems: (f,l) has the axes oriented laterally and fronto-posterior with respect to the body orientation at take off; (x,y) has the x axis parallel to the bar. Units are in 1/([sec]*10^3. The left leg was the leading leg for all the athletes. In the right column the correlation, C, between pairs of angles of the different segments are reported. The threshold was 0.85 for AA and 0.75 for GG and EE.

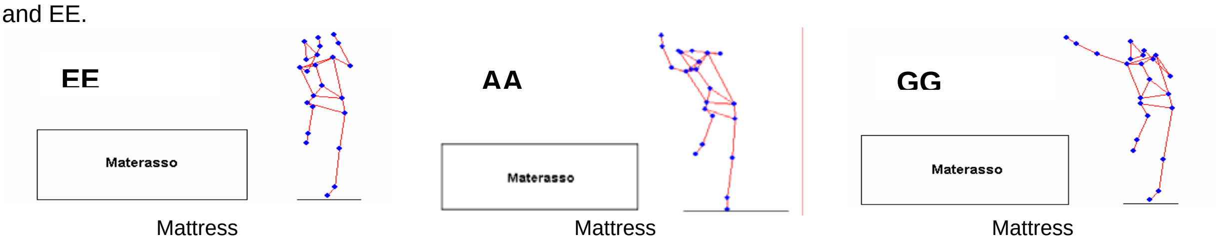


Figure 3. A 3D snapshot of the three athletes, shown with stick diagram, at take off.

To evaluate how motion was controlled by the athletes, the time course of the anatomical angles between adjacent segments was computed; the begin of the stride of the last step and the end of the take off were identified and the time course of the angles was time warped accordingly. Then we computed the correlation (C) between pairs of angles. Correlations larger than 0.85 (in absolute value) for AA and than 0.75 for GG and EE are reported in the right column of Table I. AA has overall a very high correlation value, while GG has only a few correlations. The correlation index highlights the repeatability of the kinematics gesture. From a closer look to the data, EE (Table I) exhibits a strong control over the lower body parts, while AA has more control on the upper body. This same result has been confirmed by the variability of the angles time course. An example of the knee variability for the most and least variable athlete is reported in Figure 4.

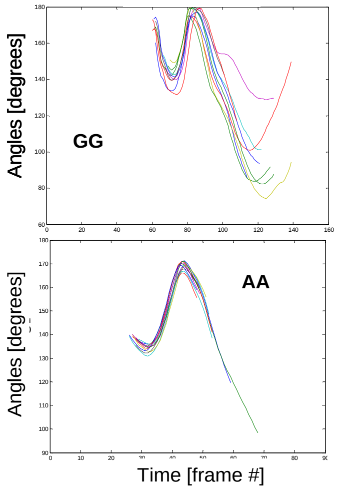


Figure 4. The time course of the knee angle of GG and AA.

DISCUSSION AND CONCLUSION: The analysis of the momentum gives few hints on how to improve the jump, especially for EE; results are in line with the study of Dapena. The motion pattern of AA and GG suggests a control over the kinematics: the relative motion of the different segments is started according to phase relationships with the other segments. This pattern can be associated to a kinematics motor program or to a template of the motion, which has been well learnt. Stereotypic kinematics patterns have been observed in well learnt natural movements like gait, and they are shown to be consistent at different speeds (Borghese et al., 1997). Moreover, at take off AA seems to better coordinate the upper body, while EE shows a higher coordination in the lower part of the body, which suggest a different master control strategy (cf. Jordan and Todorov, 2002). The higher variability of GG may suggest that her motion is mainly controlled in a dynamic (ballistic) way; that is, the focus is more on the torque to be produced than on the kinematics. Overall, these results may suggest to focus, during the training session, on the aspects which are less controlled: GG may improve by focusing more on the kinematics of the jump, AA by focusing more on the production of the torques at take off and on the control of the lower body.

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