Low-level Fall Simulation: 1-year old bouncing off bed

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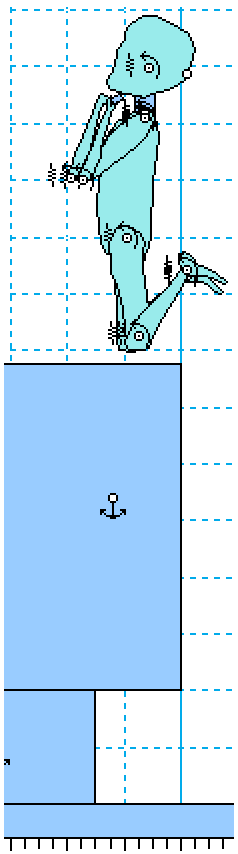
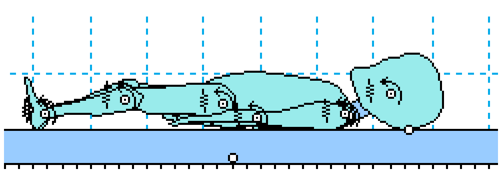
Situation

A mother reported that her large 11-month old son was bouncing on his knees on a 0.76 m (30 inch) high bed while clutching a cell phone near his neck. He fell off striking the back of his head on a hardwood floor resulting in a concussion, a subdural hematoma (SDH), and retinal hemorrhages (RH). Medical intervention was successful and the boy is now doing well. However, Child Protective Services took over custody pending a full investigation.





Working Model™ Simulation

The following simulation allows flexible joints and other variable parameters to demonstrate one of countless possible scenarios between that described by a witness and other situations where the head does not even hit the floor. It is intended as a demonstration aid that is more realistic than an artist's conception.

- Although the arms slow the descent, the head is still predicted to hit at $v_y > 4\ \mathrm{m/s}$ ≈ 9 miles/hour.

- Derived results such as accelerations and forces depend on contact time as explained in Appendix A.

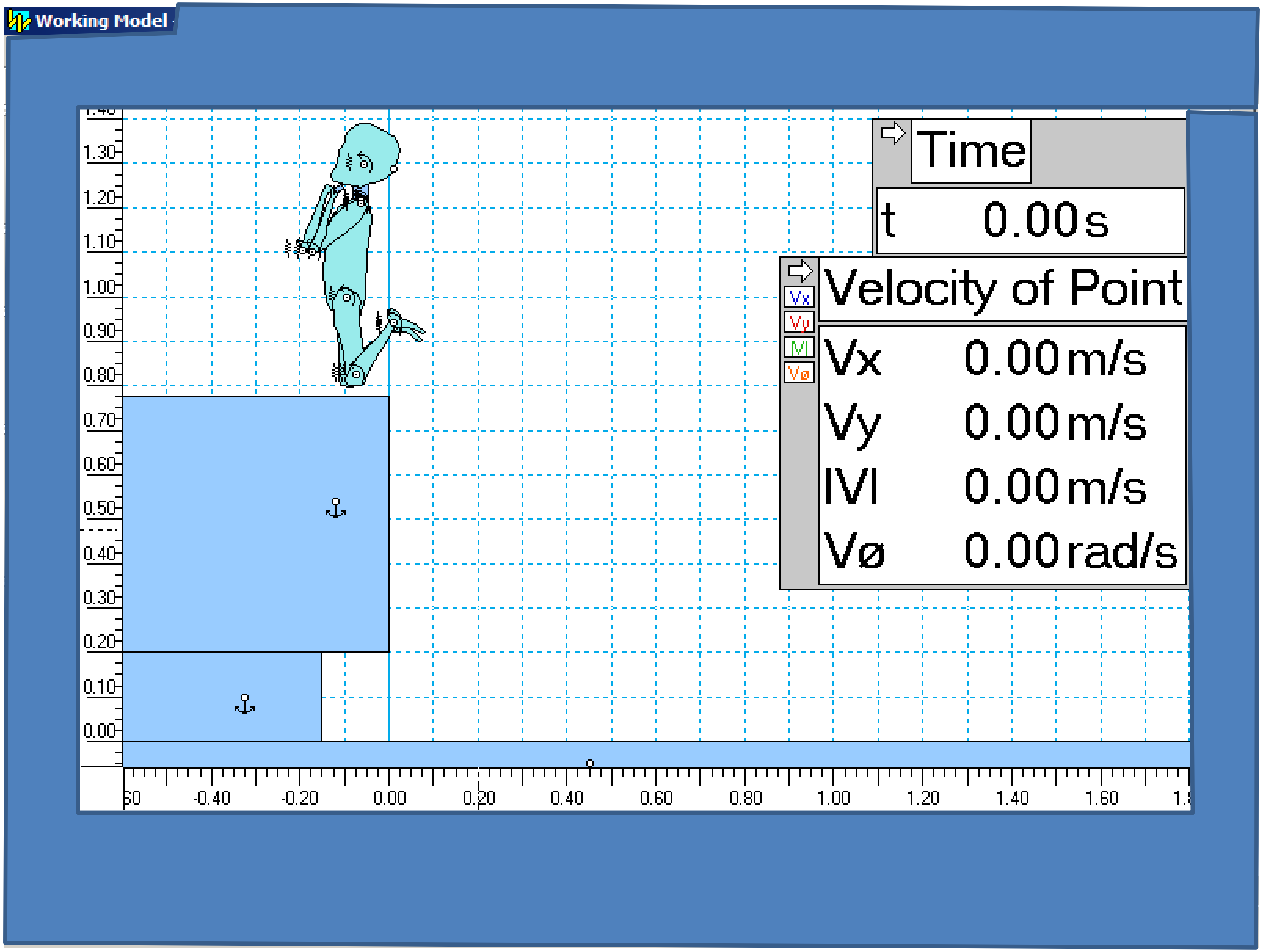
- Prediction reliability is limited by the choice of model parameters given in Appendix B (mass distribution, joint approximations, elasticity and friction) . Any changes to these parameters, initial posture, or rigidity of linked segments may change the outcome significantly.

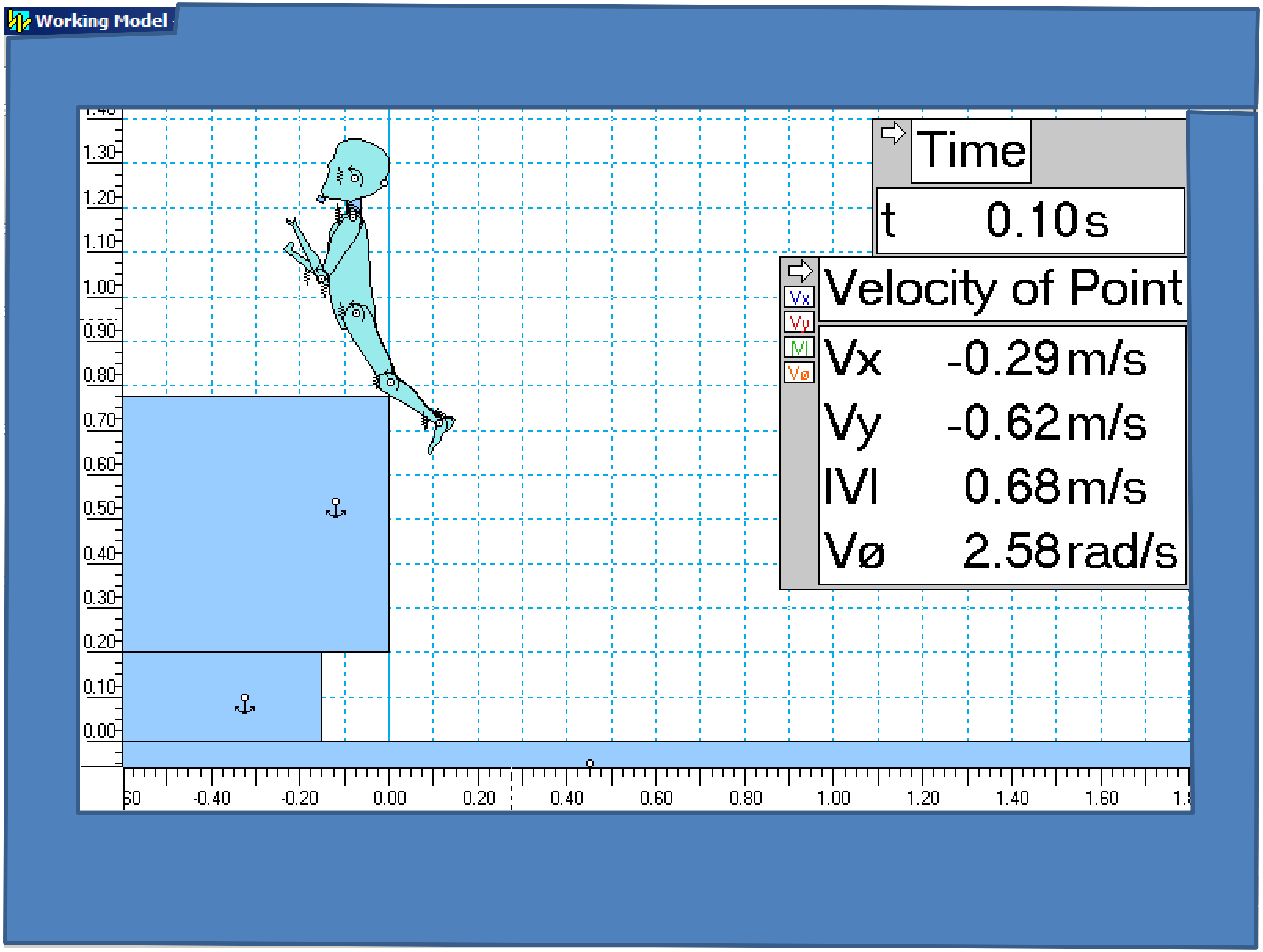
- The simulation is based on average dimensions for a 12-month old child crash-test dummy[2] with a stature of 0.74 m (29 inches) and mass of 10.0 kg (22 pound), including a 2.6 kg (5.8 pound) head. More details are given in Appendix B.

- Scale dimensions are in meters. Velocities are displayed for the initial cranial impact point. Multiply values in m/s by 2.24 to convert into miles/hour.

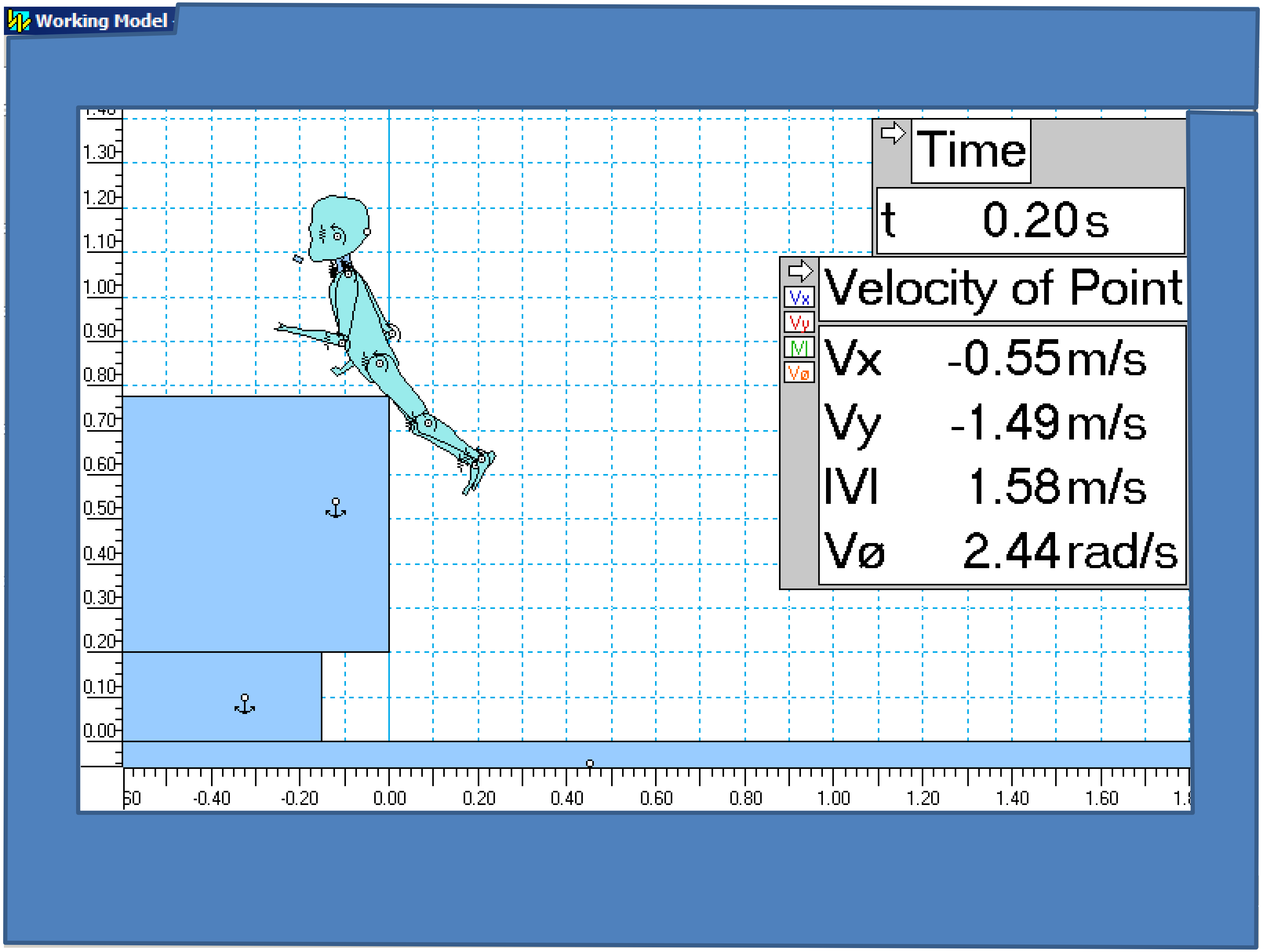
- The integrity of the software was checked by generating accurate predictions for cases with known analytical solutions. These were free-fall for a ball and toppling a long thin vertical rod about an ideal axis fixed at the bottom.

- Other computer simulations, physical models and video analysis are invited for comparison to help evaluate this simulation.

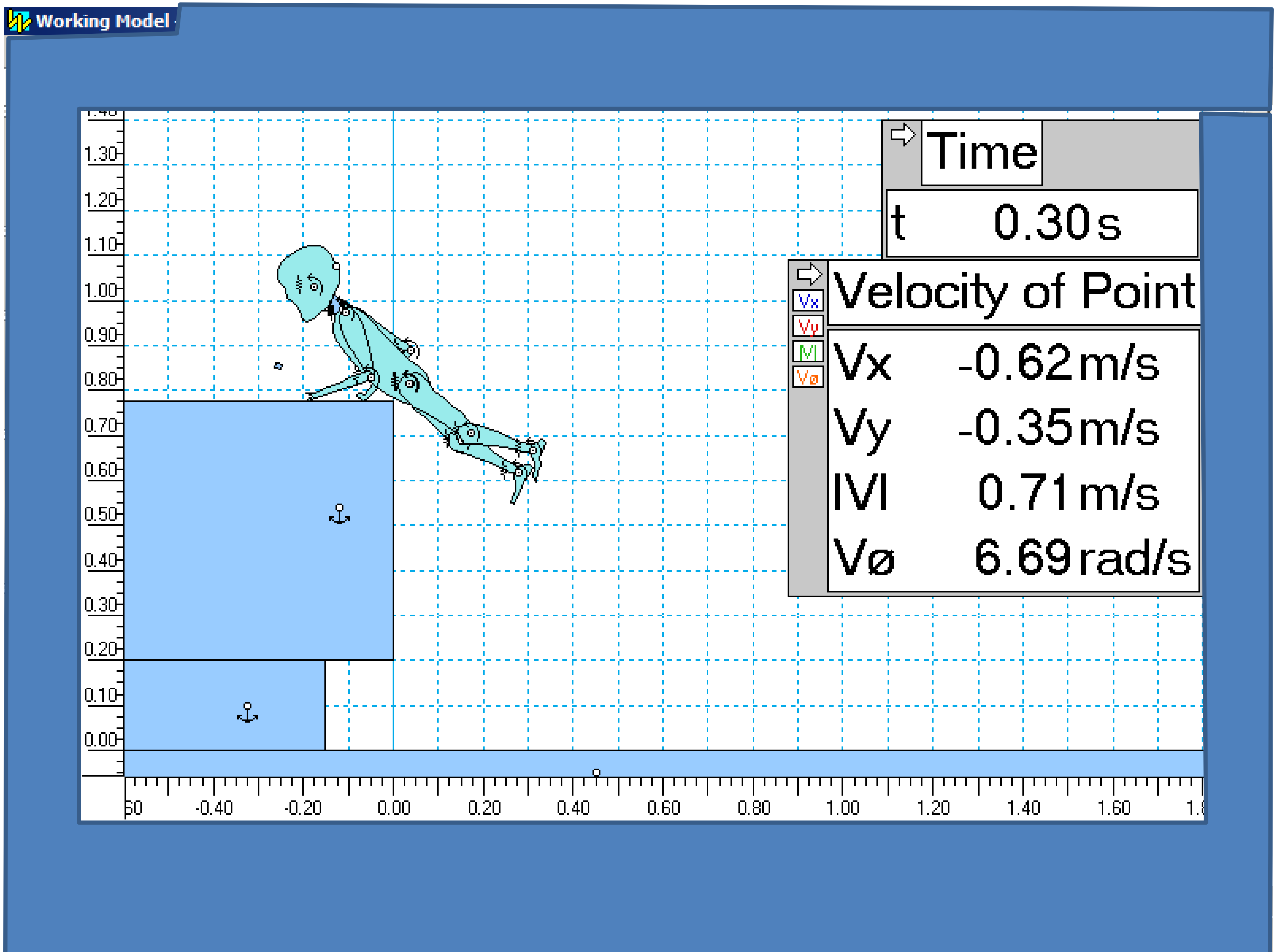

Working Model
Time
t 0.00 s
Velocity of Point
Vx
Vy
|V|
Vø
Vx 0.00 m/s
Vy 0.00 m/s
|V| 0.00 m/s
Vø 0.00 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60

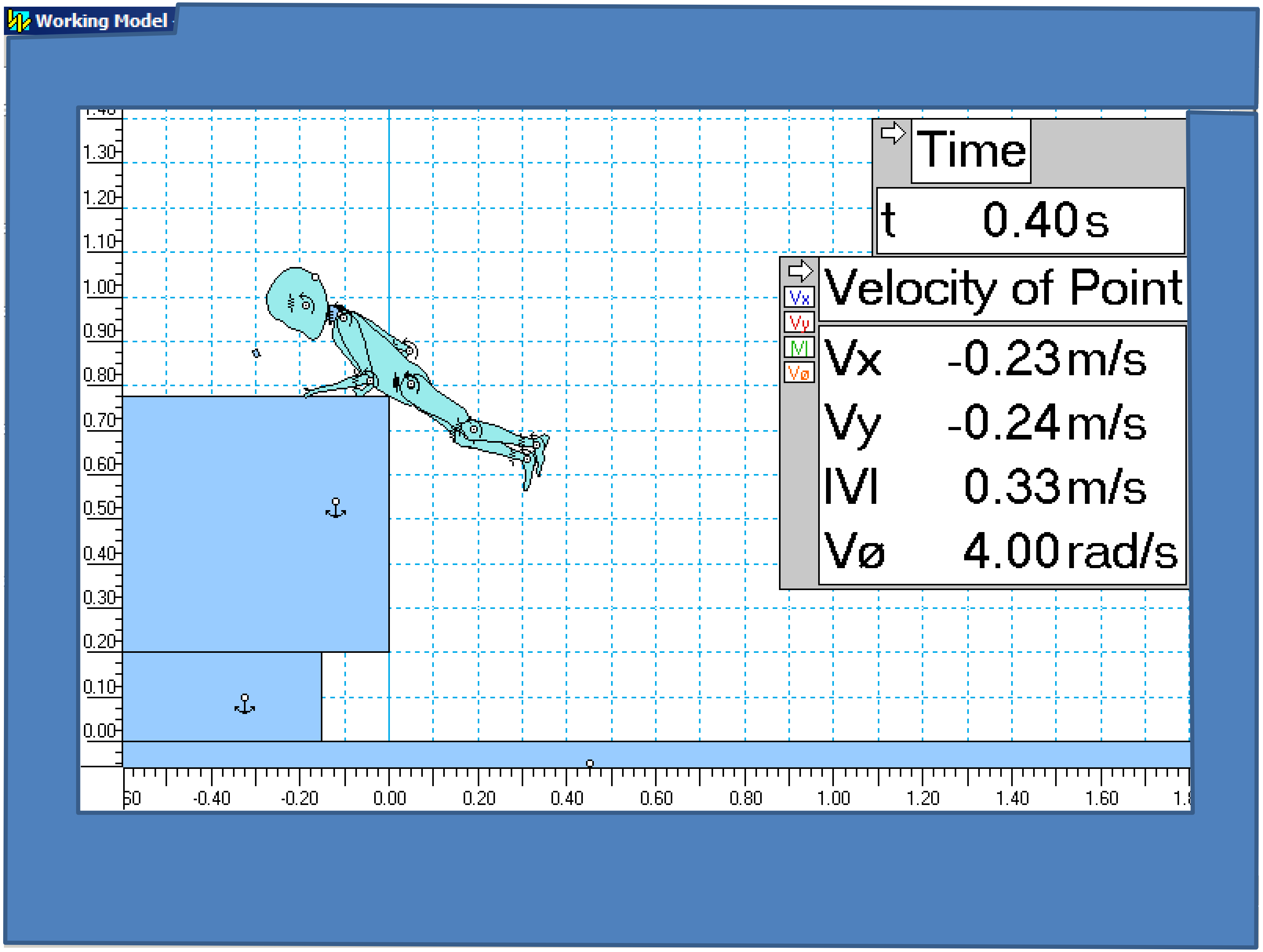


Working Model
Time
t 0.10 s
Velocity of Point
Vx -0.29 m/s
Vy -0.62 m/s
|V| 0.68 m/s
Vø 2.58 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60

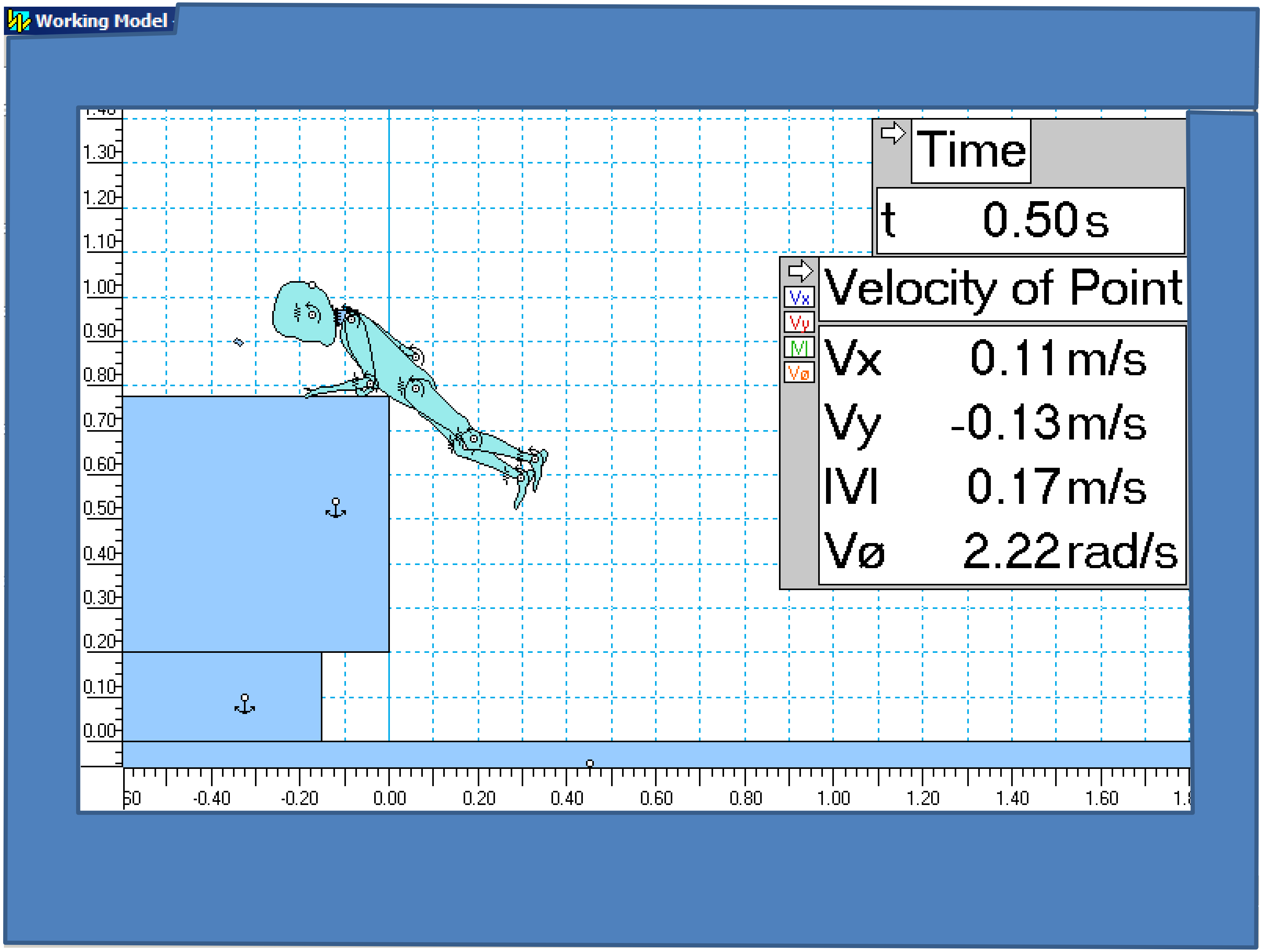


Working Model
Time
t 0.20 s
Velocity of Point
Vx -0.55 m/s
Vy -1.49 m/s
|V| 1.58 m/s
Vø 2.44 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60

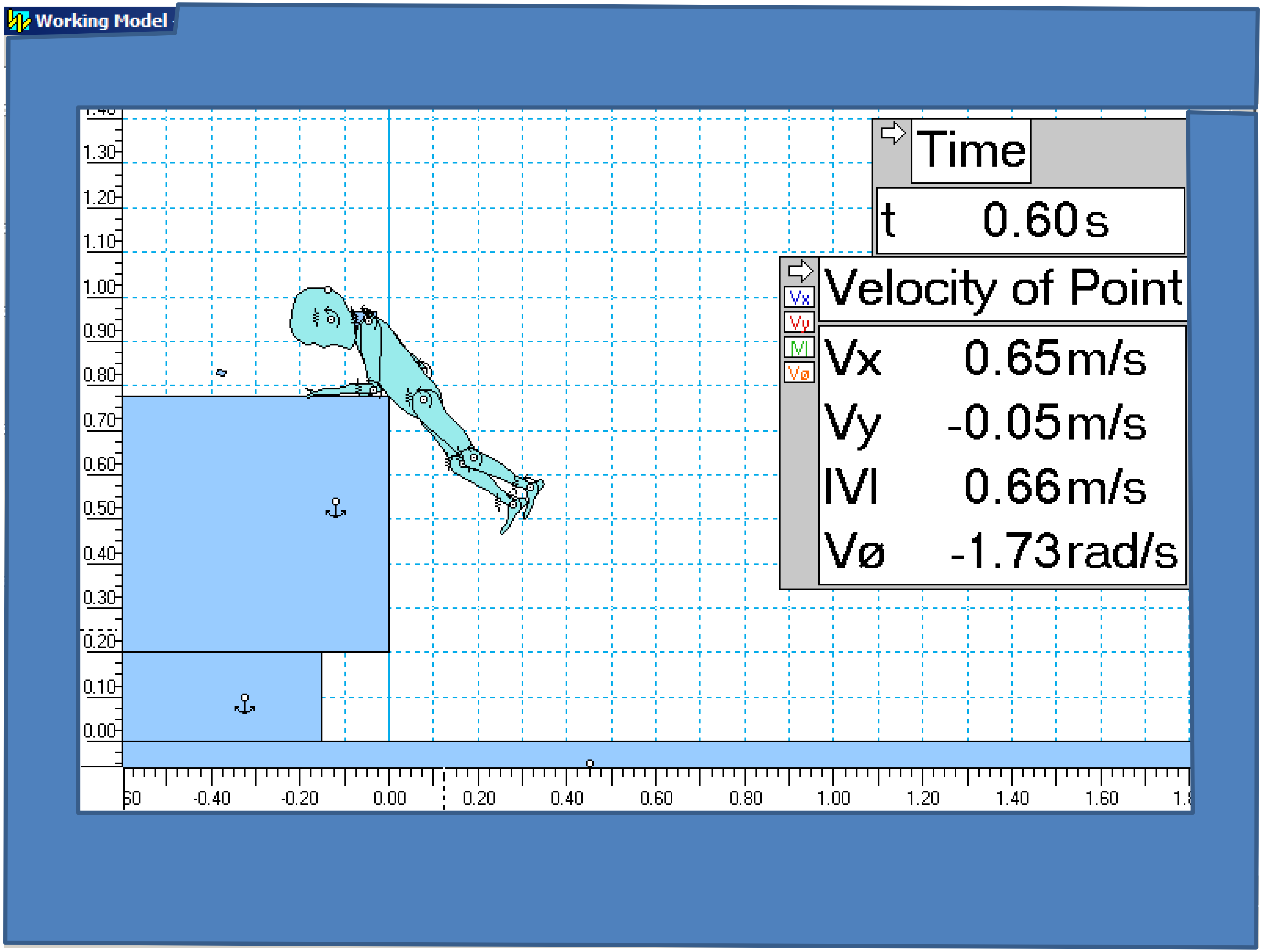

Working Model
Time
t 0.30 s
Velocity of Point
Vx -0.62 m/s
Vy -0.35 m/s
|V| 0.71 m/s
Vø 6.69 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60



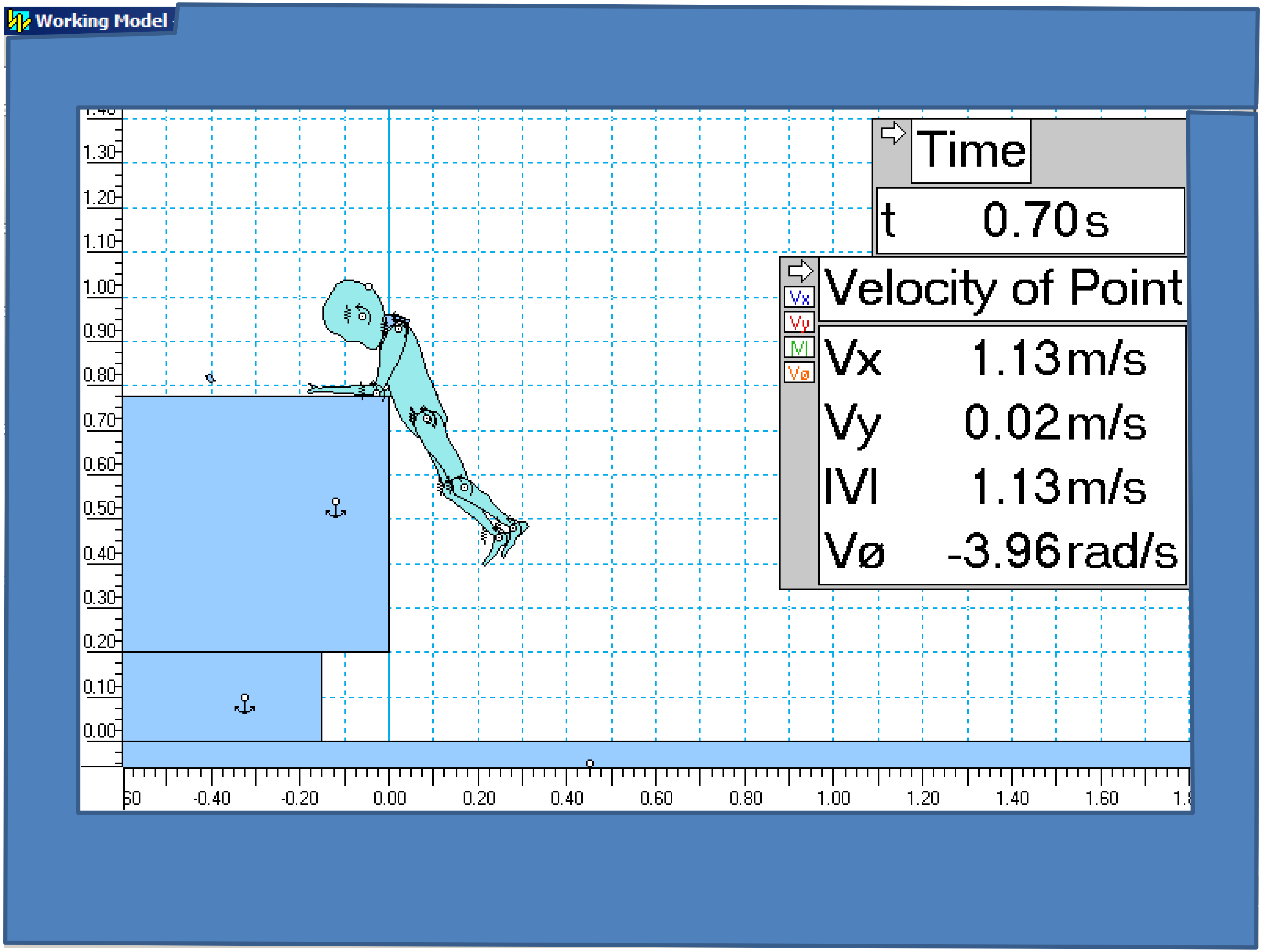
Working Model
Time
t 0.40 s
Velocity of Point
Vx -0.23 m/s
Vy -0.24 m/s
|V| 0.33 m/s
Vø 4.00 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60

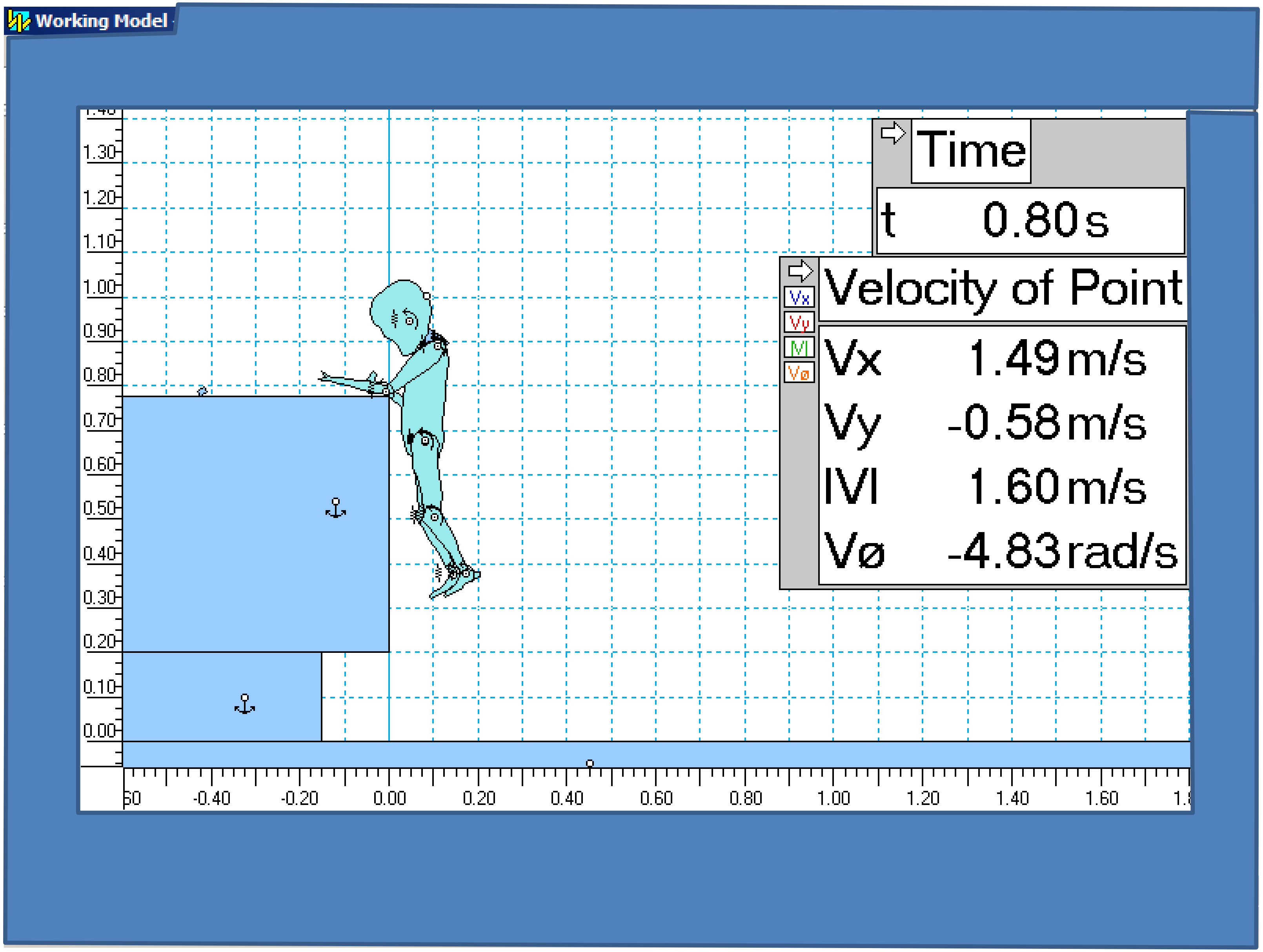


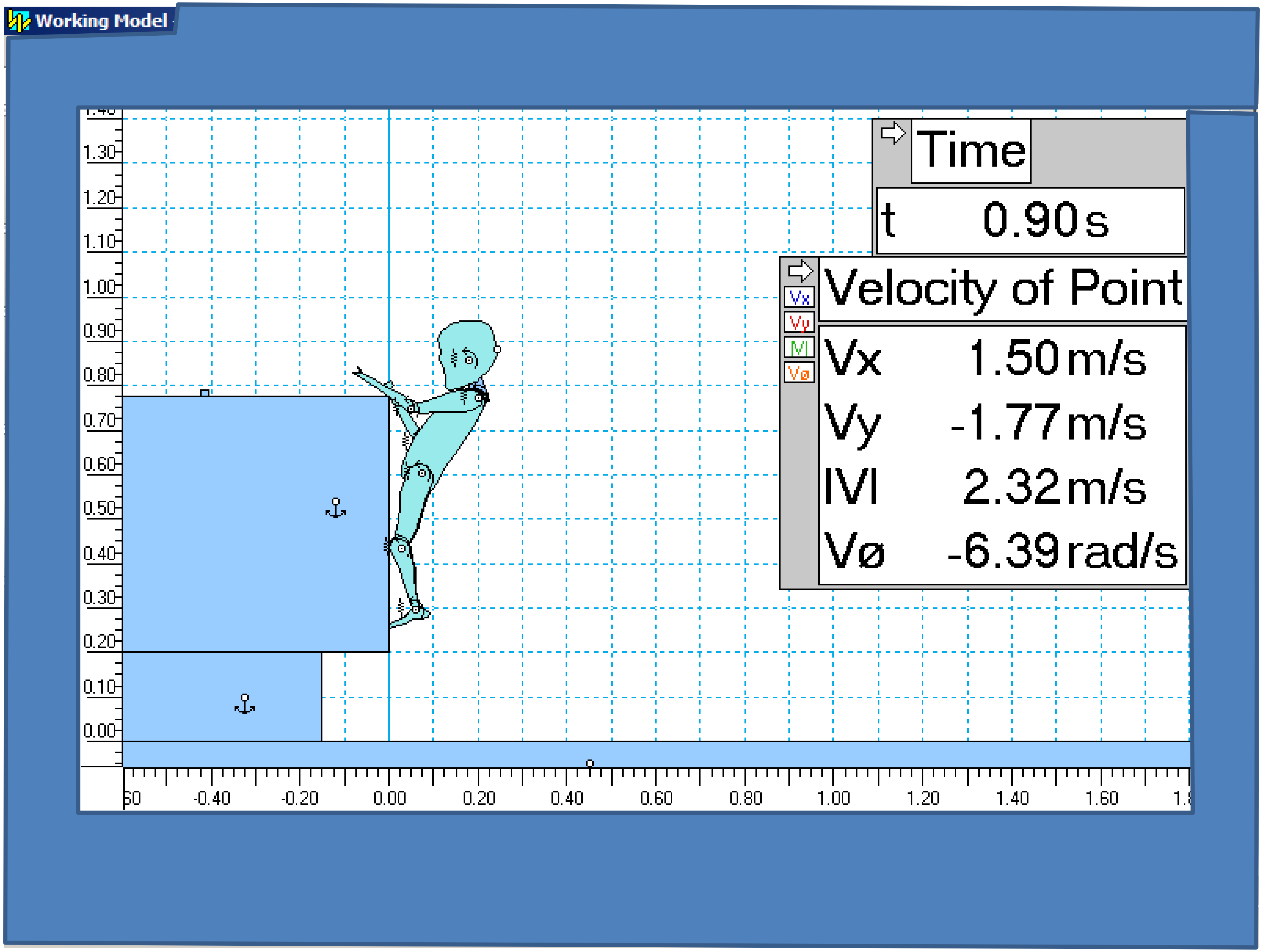
Working Model
Time
t 0.50 s
Velocity of Point
Vx 0.11 m/s
Vy -0.13 m/s
|V| 0.17 m/s
Vø 2.22 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60

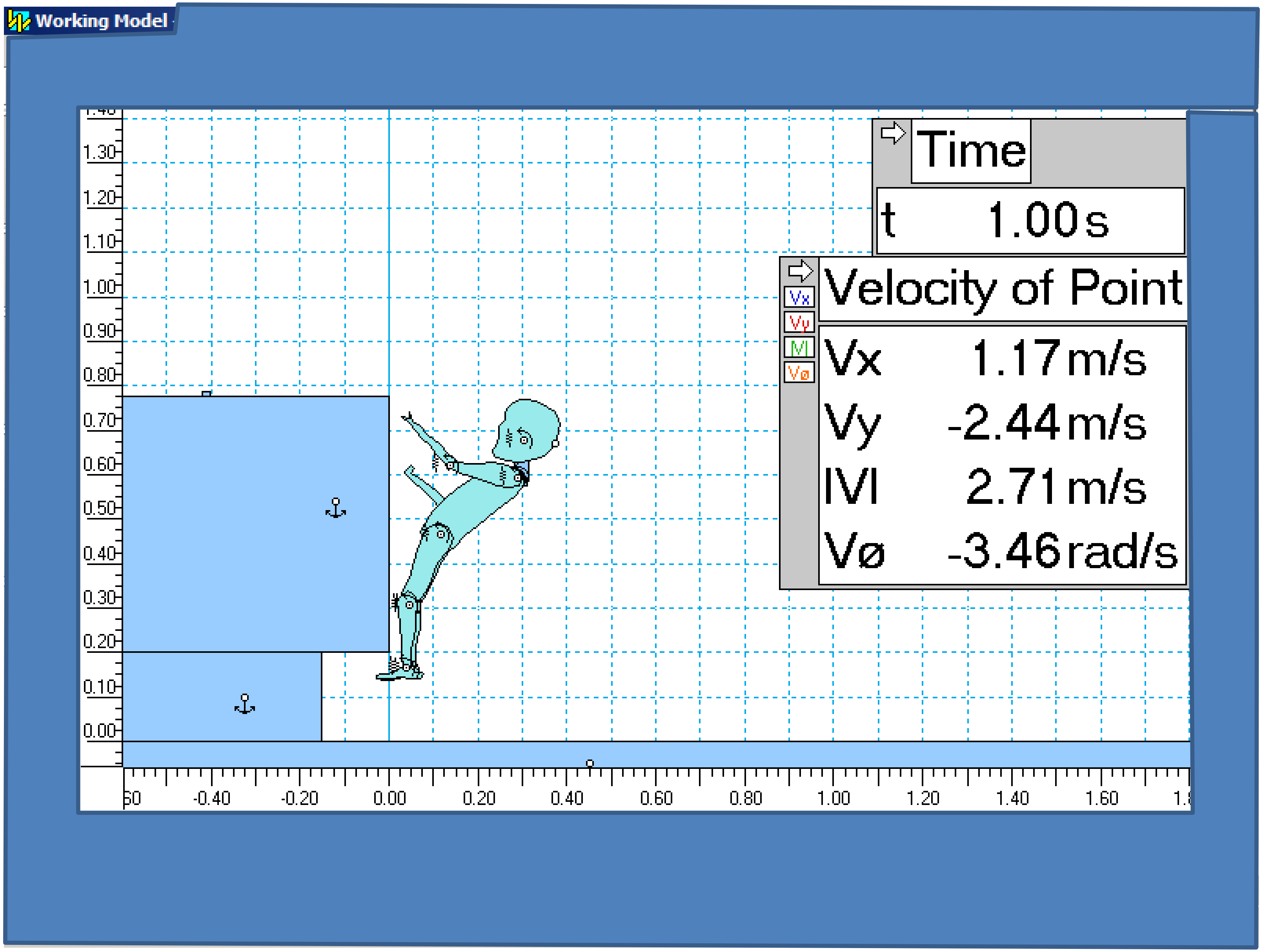


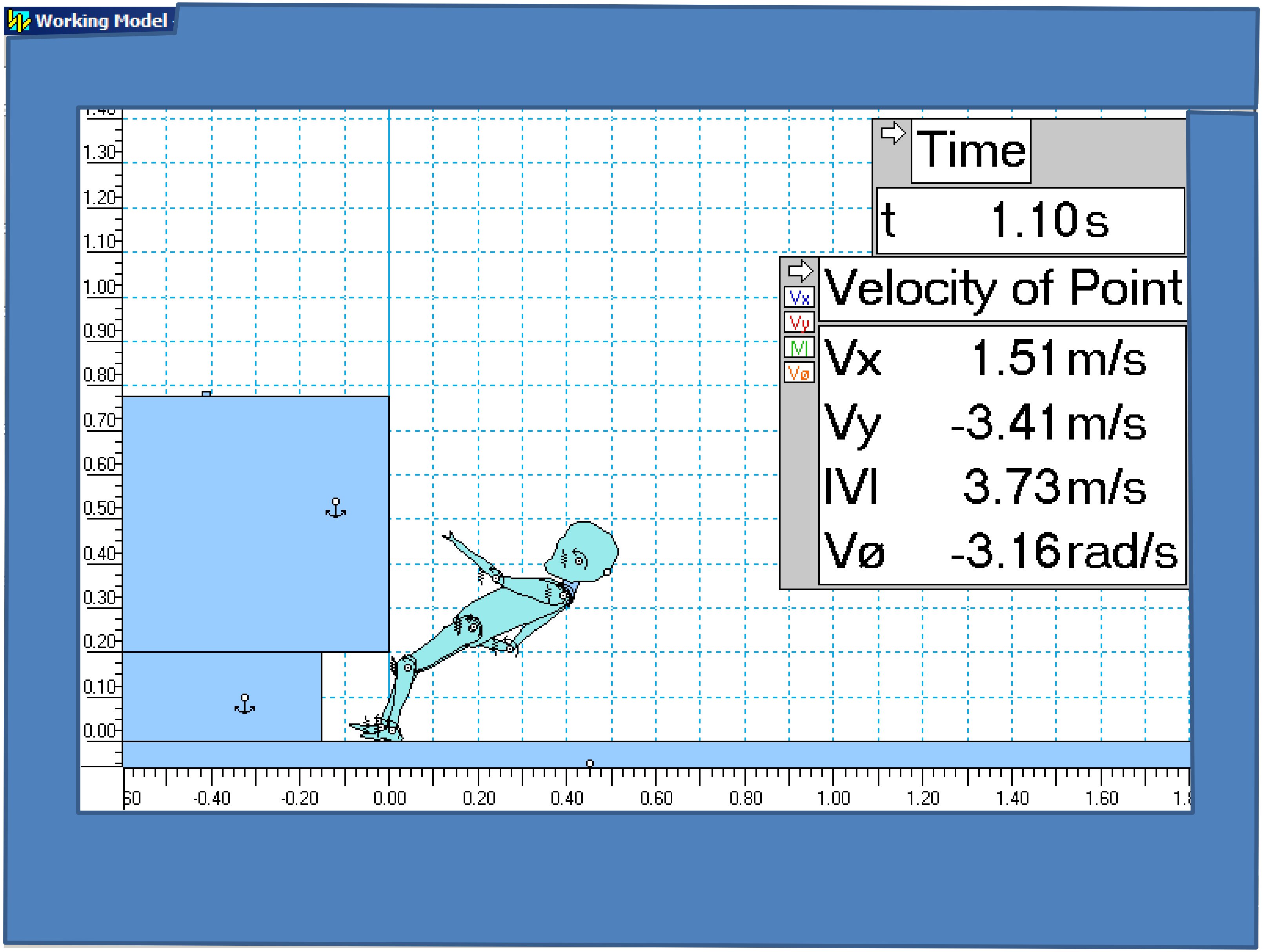
Working Model
Time
t 0.60 s
Velocity of Point
Vx 0.65 m/s
Vy -0.05 m/s
|V| 0.66 m/s
Vø -1.73 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60


Working Model
Time
t 0.70 s
Velocity of Point
Vx 1.13 m/s
Vy 0.02 m/s
|V| 1.13 m/s
Vø -3.96 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60

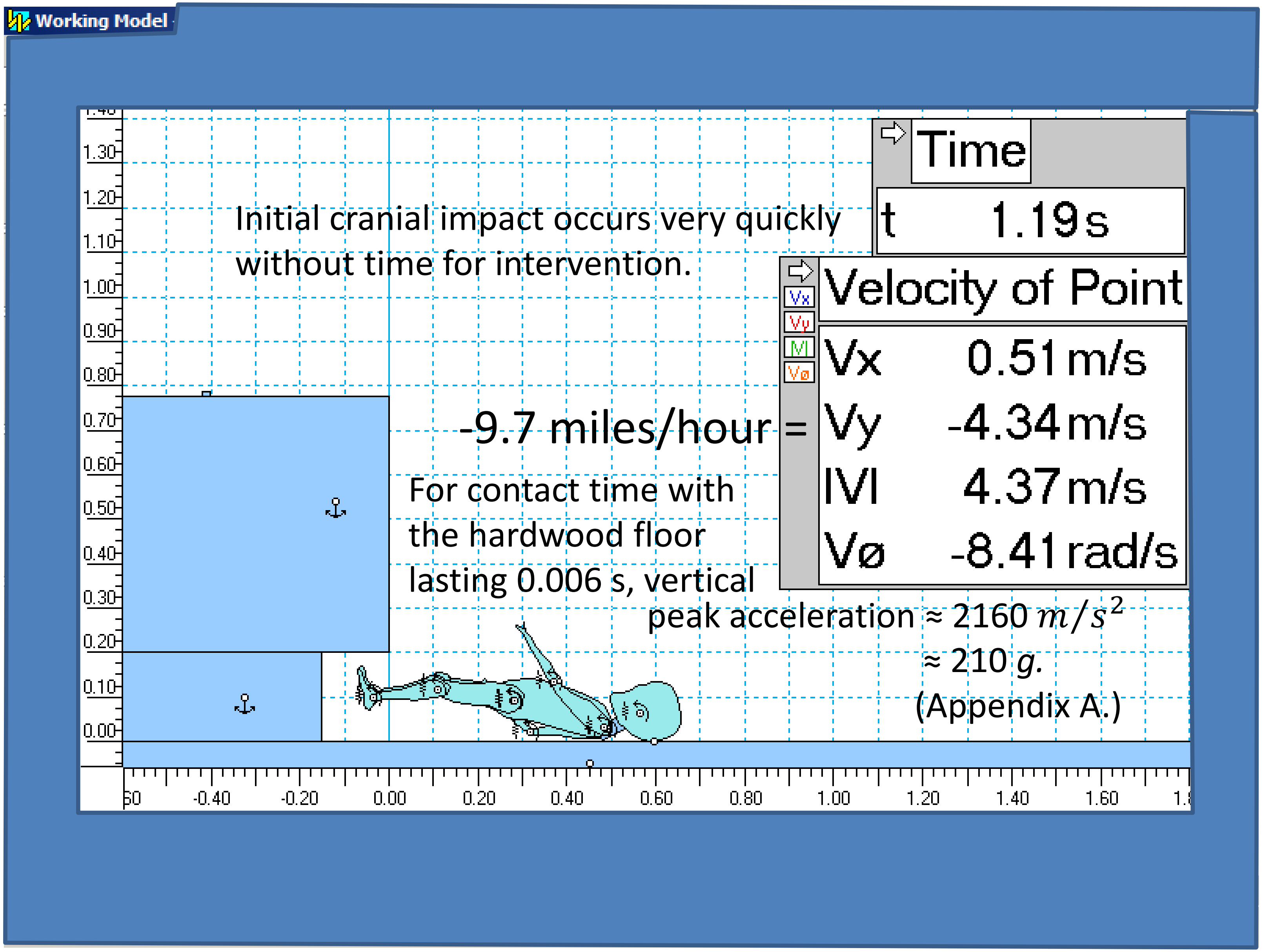

Working Model
Time
t 0.80 s
Velocity of Point
Vx 1.49 m/s
Vy -0.58 m/s
|V| 1.60 m/s
Vø -4.83 rad/s

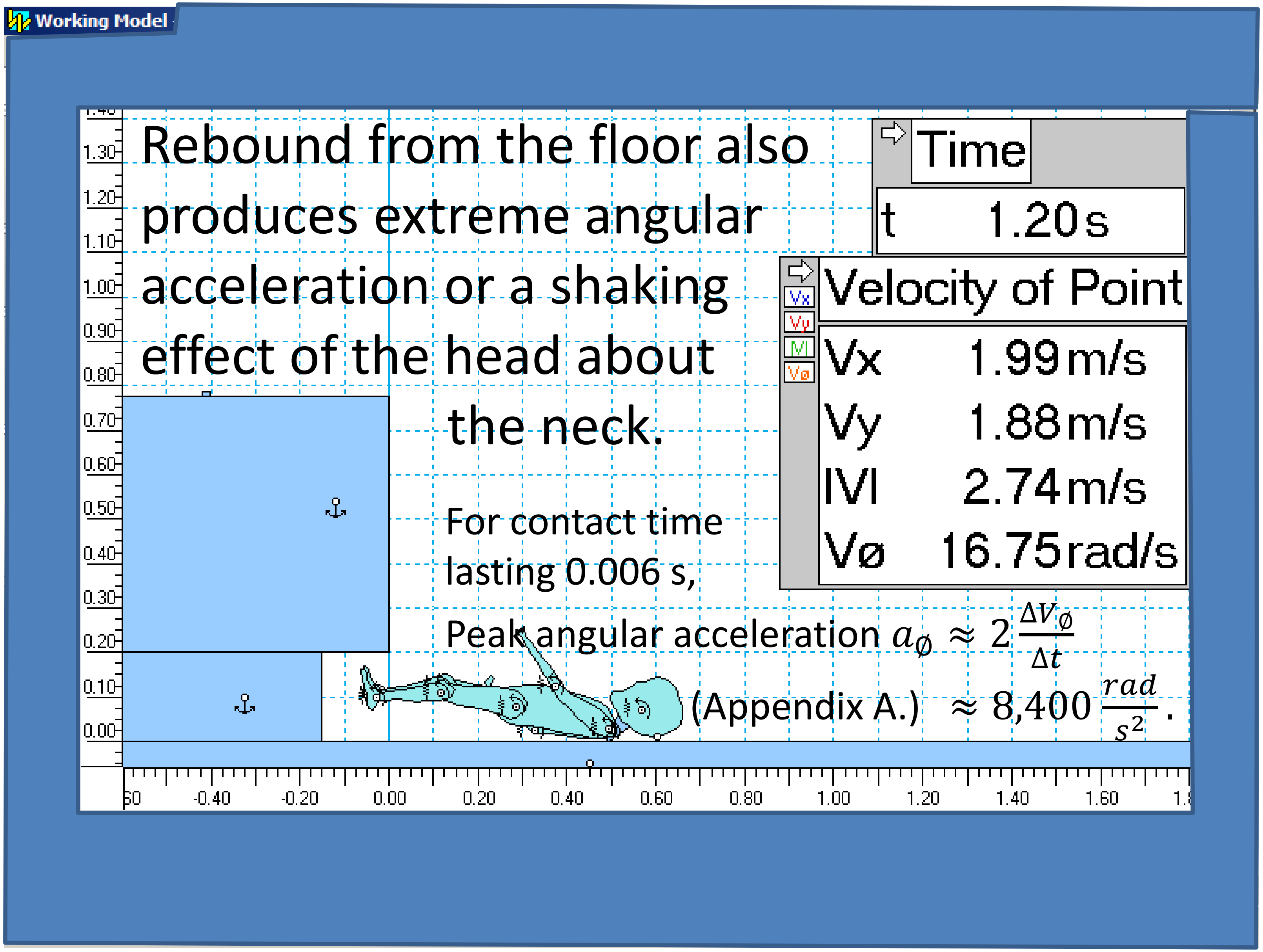

Working Model
Time
t 0.90 s
Velocity of Point
Vx 1.50 m/s
Vy -1.77 m/s
IVI 2.32 m/s
Vø -6.39 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60


Working Model
Time
t 1.00 s
Velocity of Point
Vx
Vy
|V|
Vø
Vx 1.17 m/s
Vy -2.44 m/s
|V| 2.71 m/s
Vø -3.46 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60



Working Model
Time
t 1.10 s
Velocity of Point
Vx 1.51 m/s
Vy -3.41 m/s
|V| 3.73 m/s
Vø -3.16 rad/s

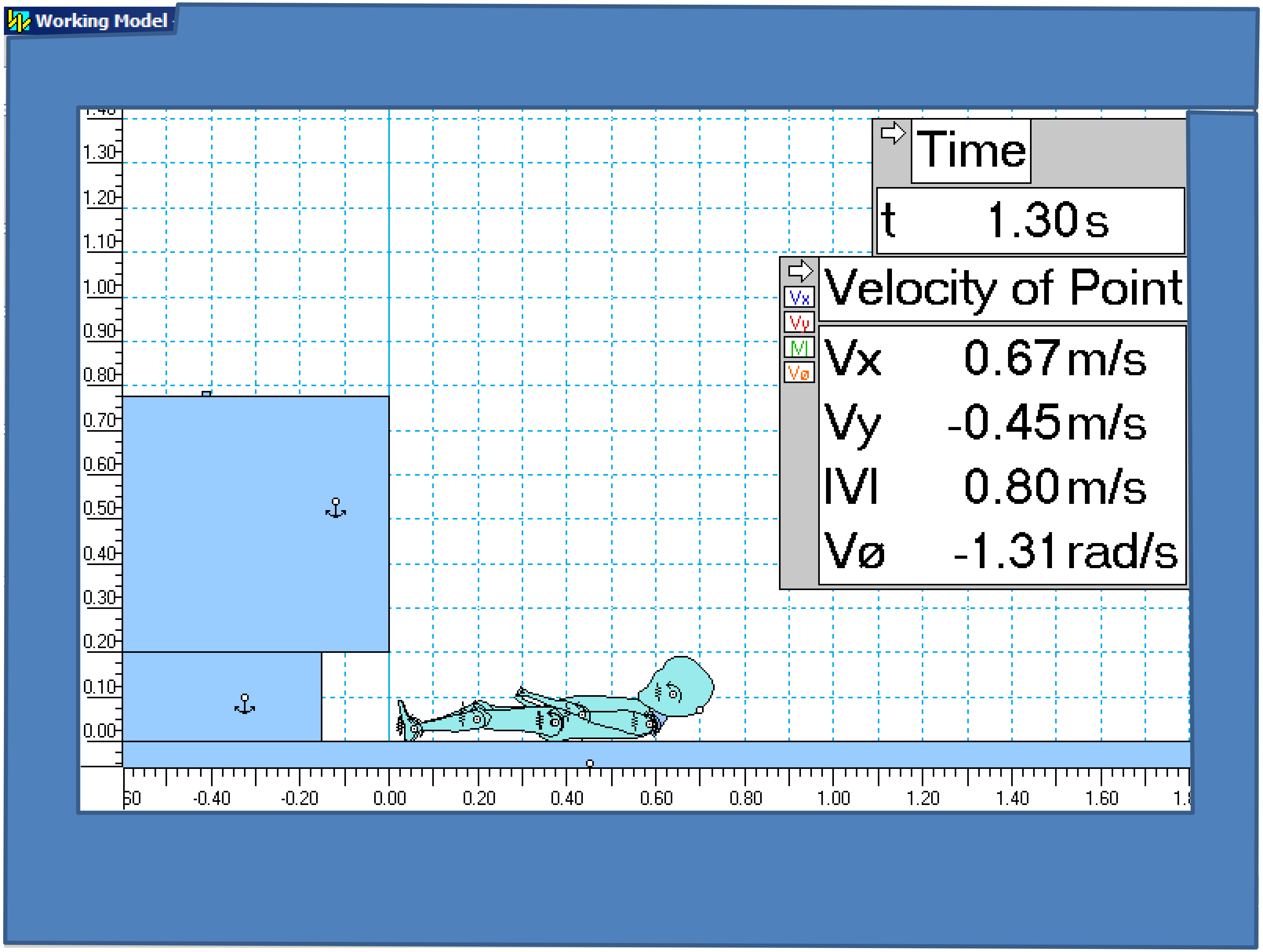

Working Model
Time
t 1.19 s
Velocity of Point
Vx 0.51 m/s
Vy -4.34 m/s
|V| 4.37 m/s
Vø -8.41 rad/s
Initial cranial impact occurs very quickly without time for intervention.
-9.7 miles/hour =
For contact time with the hardwood floor lasting 0.006 s, vertical peak acceleration ≈ 2160 m/s^2
≈ 210 g.
(Appendix A.)

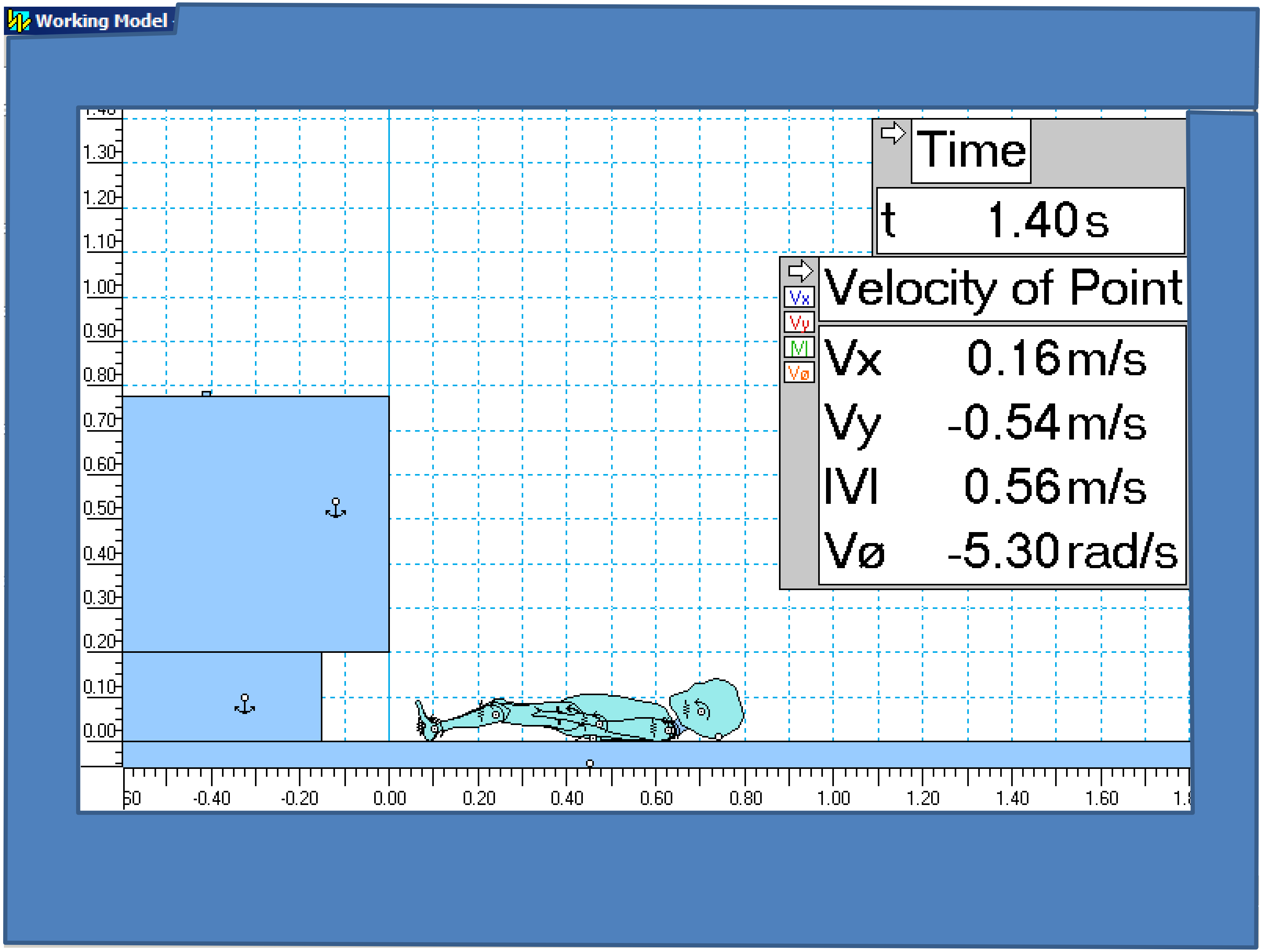


Rebound from the floor also produces extreme angular acceleration or a shaking effect of the head about the neck.

For contact time lasting 0.006 s,

Peak angular acceleration $a_{\emptyset} \approx 2\,\frac{\Delta V_{\emptyset}}{\Delta t}$ (Appendix A.) $\approx 8{,}400\,\frac{rad}{s^2}$.


Working Model
Time
t 1.30 s
Velocity of Point
Vx 0.67 m/s
Vy -0.45 m/s
|V| 0.80 m/s
Vø -1.31 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.40
-0.20
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60



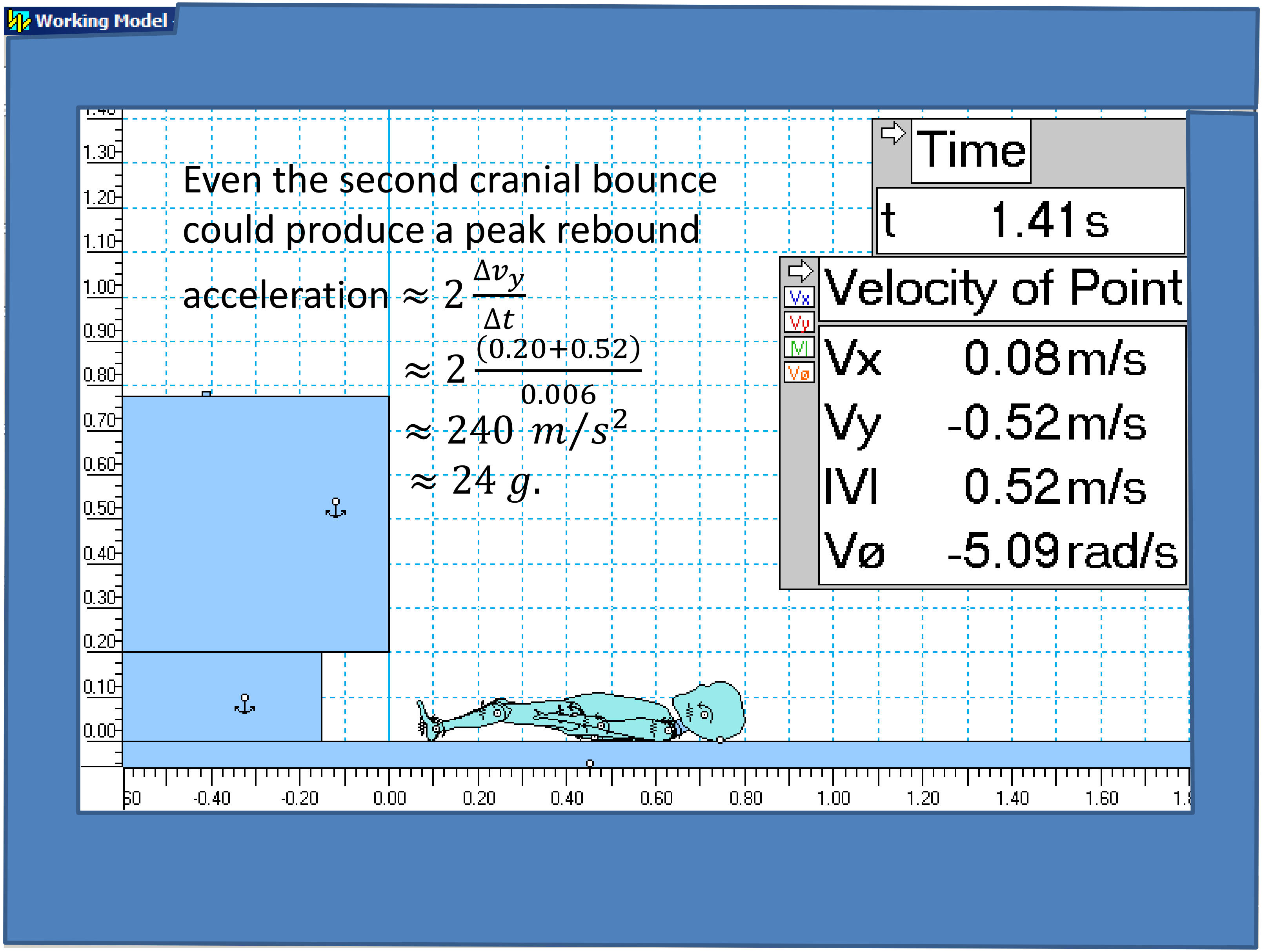
Working Model
Time
t 1.40 s
Velocity of Point
Vx 0.16 m/s
Vy -0.54 m/s
|V| 0.56 m/s
Vø -5.30 rad/s

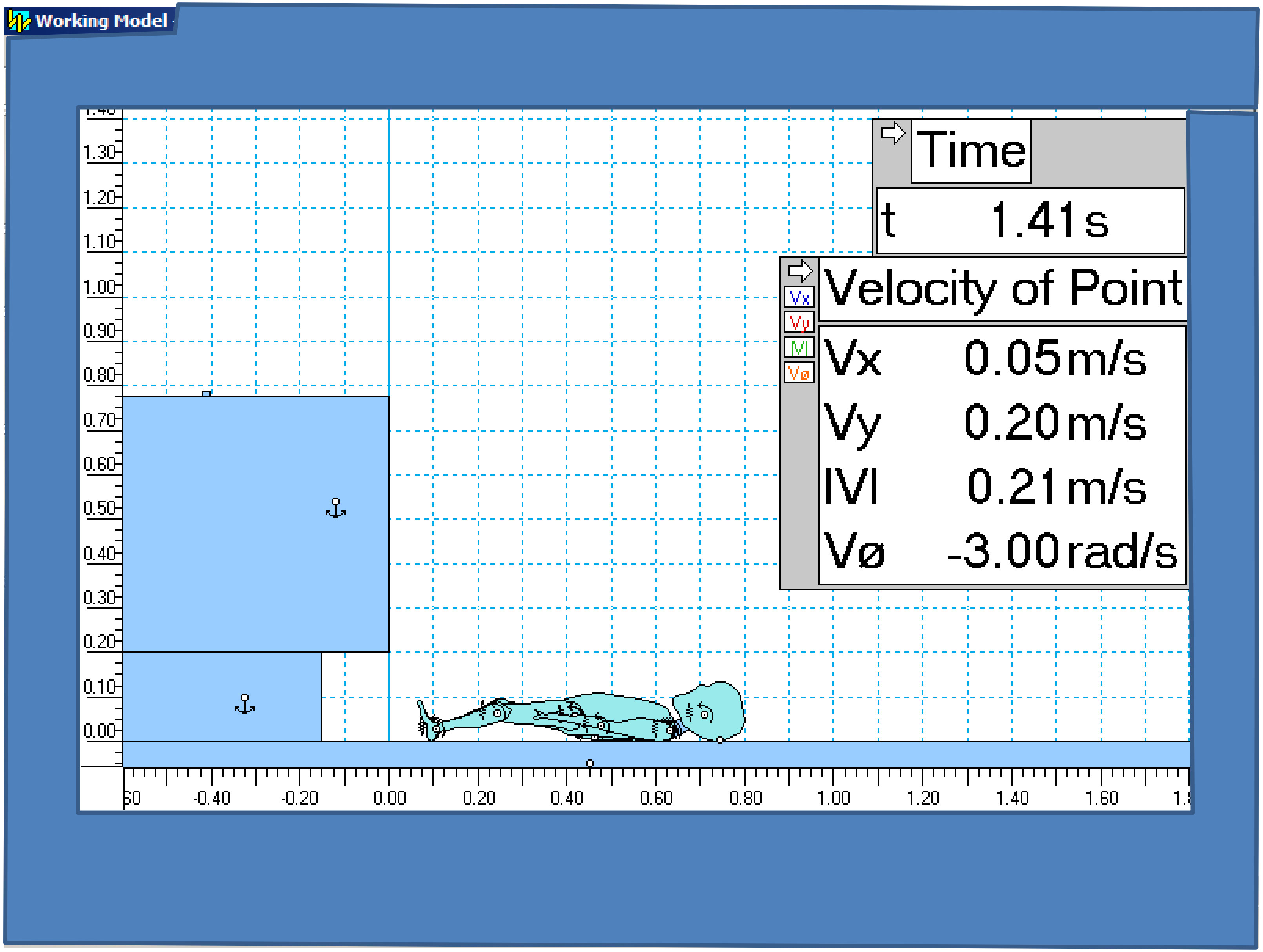
Even the second cranial bounce could produce a peak rebound acceleration $\approx 2\frac{\Delta v_y}{\Delta t}$

$$\approx 2\frac{(0.20+0.52)}{0.006}$$

$$\approx 240\ m/s^2$$

$$\approx 24\ g.$$




Working Model
Time
t 1.41 s
Velocity of Point
Vx
Vy
|V|
Vø
Vx 0.05 m/s
Vy 0.20 m/s
IVI 0.21 m/s
Vø -3.00 rad/s
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
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1.00
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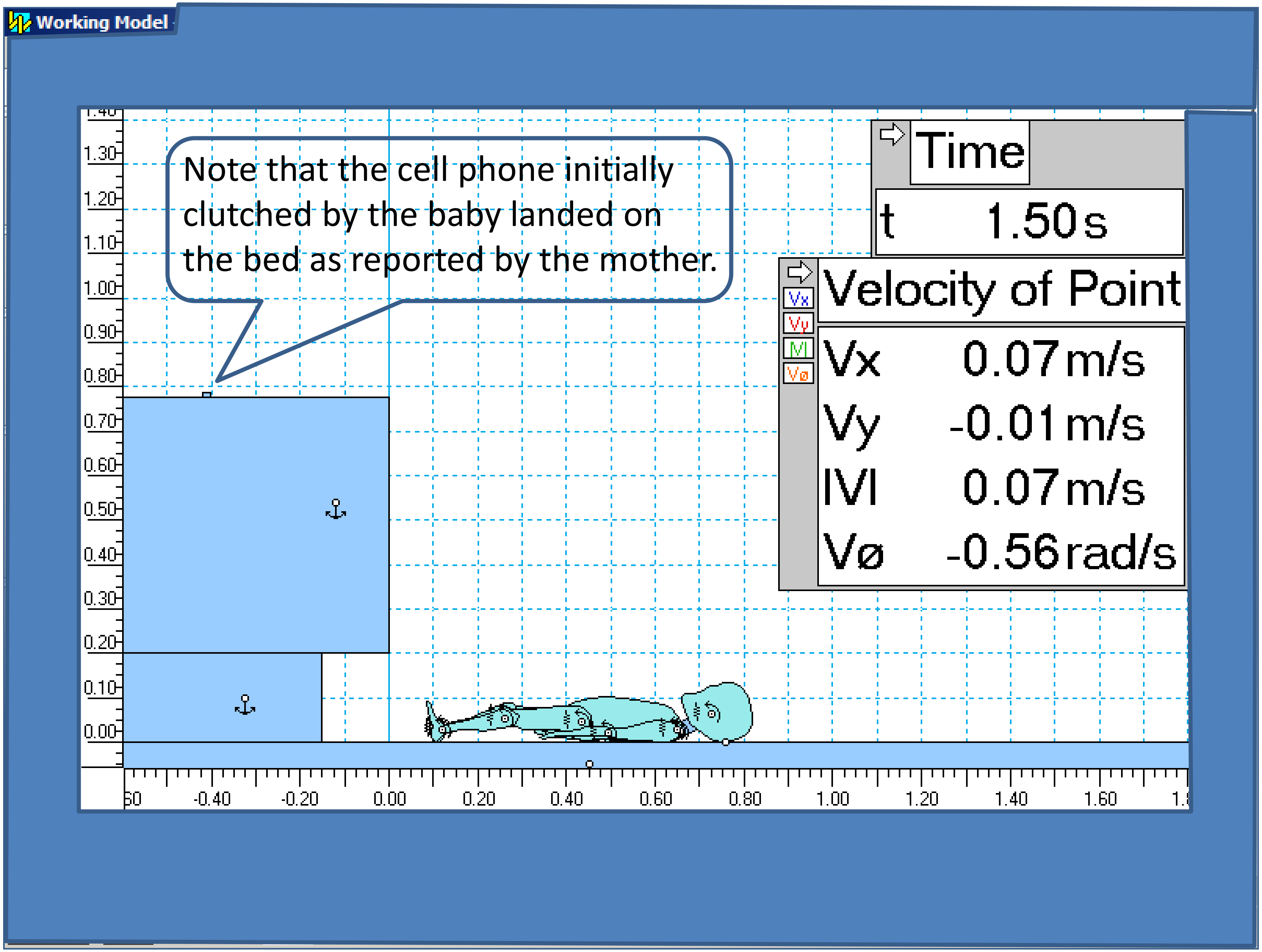
1.60



Working Model
Note that the cell phone initially clutched by the baby landed on the bed as reported by the mother.
Time
t 1.50 s
Velocity of Point
Vx 0.07 m/s
Vy -0.01 m/s
|V| 0.07 m/s
Vø -0.56 rad/s

Conclusion

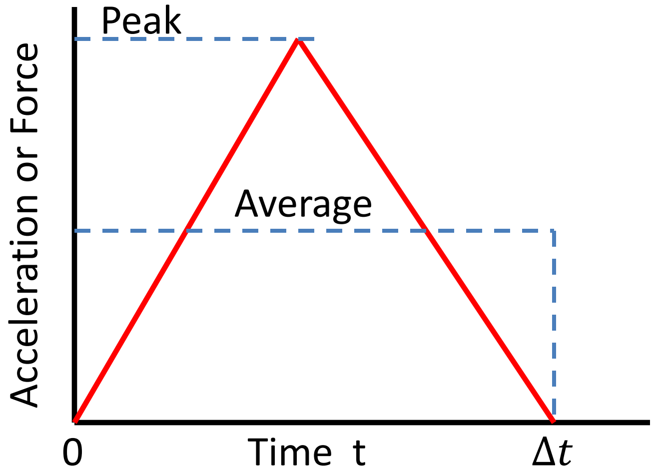
This simulation clearly shows the potential for severe head injuries from low-level falls. The resulting accelerations and forces for the first impact are more than 10 times greater than those that can usually be produced by manually shaking a realistic dummy.[3, 4] Even the second bounce exceeds that due to shaking.

Appendix A. Physics Relationships

- By definition, the average acceleration in the vertical dimension $\langle a_y \rangle \equiv \frac{\Delta v_y}{\Delta t}$, where Δv_y is the change in velocity and Δt is the interaction time with the floor.

- A toddler head colliding with a rigid surface has $\Delta t \approx 0.005\ s$.[3,4] Moderate padding extends this to $\Delta t \approx 0.020\ s$. $\Delta t = 0.006\ s$ was chosen as a reasonable value for a hardwood floor.

- As illustrated, a linear approximation of the acceleration or force between the floor and the head shows that the maximum or peak value is about twice the average.[4, 5]



- Divide accelerations in m/s^2 by $g = 9.8\ m/s^2$ to convert into *g's.* Multiply accelerations by mass to convert into forces.

Appendix B. Model Specifications

$$(\text{typical } 12-\text{month old baby})^2$$

Body Segment	Mass (kg)	Static friction coefficient	Kinetic friction coefficient	Elasticity
Head	2.64	0.5	0.4	0.5
Neck	0.38	0.3	0.3	0.5
Torso	3.68	0.5	0.4	0.1
Combined upper arms	0.60	0.3	0.3	0.5
Combined lower arms with hands	0.60	0.9	0.8	0.5
Combined upper legs	1.00	0.3	0.3	0.5
Combined lower legs	0.80	0.3	0.3	0.1
Combined feet	0.20	0.5	0.4	0.5
TOTAL	9.90 kg			

- By definition, elasticity or coefficient of restitution ≡ |rebound velocity / impact velocity|. The bed and floor are assigned values of 0.5, and the body segments are given above.

- The torso was also given an initial downwards velocity of 0.5 m/s.

Joint	Torque = k r k in N-m/rad	Initial Rotation In rad	Rotational Damping (N-m-s/rad)
Head-Neck	1.0	0	1.0
Neck-Torso	1.0	0	1.0
Shoulders	1.0	1.5	1.0
Front Elbow Back Elbow	2.0 2.0	-3.0 +3.0	1.0 1.0
Hips	10.0	0	1.0
Knees	10.0	-2.0	0.1
Ankles	10.0	0	1.0

- Rotational joint values were chosen for realistic response since standards are impossible for a variable organism.

- Kutta-Merson with 0.0001 second integration steps provides accuracy and model stability. Only one step out of every thousand is illustrated.

References

1. Baker, Susan P., O'Neill, Brian, Ginsburg, Marvin J., and Li, Guohua. *The Injury Fact Book* (Oxford University Press 1992), 2nd ed., p.140

2. http://www.humaneticsatd.com/crash-test-dummies/children

3. Ommaya A K, Goldsmith W and Thibault L. Biomechanics and neuropathology of adult and paediatric head injury. British Journal of Neurosurgery 2002; 16(3): 220-242

4. Goldsmith W and Plunkett J. A biomechanical analysis of the causes of traumatic brain injury in infants and children. The American Journal of Forensic Medicine and Pathology June 2004; 25(2): 89-100

5. Cross, Rod. The Bounce of a Ball. American Journal of Physics March 1999; 67 (3): 222-227