# Development of Concentric-only Exercise Machine with Estimation of Whole Body Dynamics

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Abstract: Recently, the effects of concentric and eccentric training have been evaluated to determine how to make exercise more effective. Some researchers have reported that concentric exercise increases the concentric strength. In this case, concentric exercise may enhance the concentric force performance with or without lower muscle damage and pain. Therefore, we developed a concentric training machine for lower extremities that we call iSAAC. This machine has an electromagnetic brake to generate a safe resistance load for exercise. The magnitude of the resistance power is less than or equal to the human-applied power. We calculated whole body dynamics such as the joint torque and work of the lower extremities based on the inverse dynamics of the whole body without constraints. We verified the effectiveness of the system through squat-like knee extension exercise and inverse dynamics analysis. The proposed machine provided safe training for concentric knee extension and information on the whole body dynamics during exercise.

## 1 INTRODUCTION

Daily exercise is important for people to keep or improve their motor ability. Many people go to fitness gyms and use the latest training machines. The merit of machine training is that these machines let the user utilize a heavy training load. Various intelligent exercise machines have been developed to enhance the training effect on specific motor abilities.

Concentric and eccentric power generation are important factors in deciding a training menu. Some researchers have reported that eccentric training increases muscle hypertrophy or muscle damage (Seger et al., 1998; Gonzalez-Izal et al., 2014). Others have reported that there is no significant difference in results between concentric and eccentric training (Ben-Sira et al., 1995). Blazevich et al. and Cadore et al. reported that a concentric training group showed a greater increase in the concentric torque than an eccentric training group (Blazevich et al., 2007; Cadore et al., 2014). Cadore et al. reported that the eccentric training group showed a greater increase in the eccentric torque than the concentric exercise group (Cadore et al., 2014), whereas Blazevich et al. reported that there was no significant difference in the increase in eccentric torque between the concentric and eccentric training groups (Blazevich et al., 2007). These results show that concentric exercise may enhance the concentric force performance with or without lower muscle damage and pain. Therefore, the effect of concentric training alone needs to be verified.

In general, most traditional cyclic resistance training includes both concentric and eccentric power generation. Therefore, a special exercise machine is required for cyclic unilateral concentric or eccentric resistance training.

In this paper, we introduce a concentric exercise machine test bed based on a passive power supply. We call this the Intelligent System of Advanced Actuation for Concentric training (iSAAC). The iSAAC adopts electromagnetic brakes as a power source for the training load. Many researchers have focused on safety in the development of machines that will interact with humans because the machine must not harm the human body. We selected a brake as the safety actuation device. The magnitude of the reaction force is less than or equal to the applied force, and its direction is opposite to that of the motion. Therefore, the braking force is suited for concentric training resistance.


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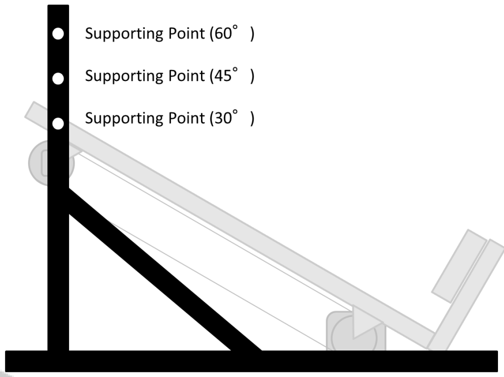
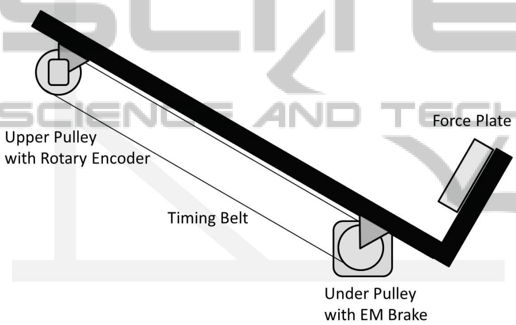
(a) iSAAC.

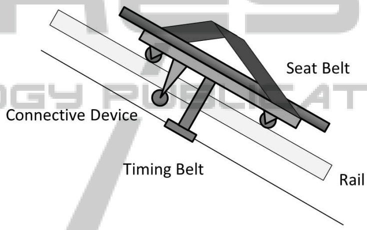



(b) Base unit.






(c) L-shaped unit.




(d) Sliding board.

Figure 1: Image of iSAAC and its principal composition elements.

Second, a training machine can provide the user with a unique resistance load. Many developed machines target the exercise of a single joint, such as the knee or elbow, for safety or portability training (Shufang et al., 2006; Kikuchi et al., 2009; Nikitczuk et al., 2010). Moromugi et al. proposed a multi-joint exercise machine based on a muscle stiffness sensor (Moromugi et al., 2006). The resistance load is generated via sensory information from the specific muscle activity. The main target of our system is multi-joint exercises for knee extension, such as squat exercises. Therefore, the training load is determined by the knee angle during exercise.

This machine has a movable seat, where the user lies on his or her back. The user's trunk is fixed to the seat by two belts. The electromagnetic brake applies a resistance force to the trunk through this seat. Most sensors are embedded in the machine; the user only wears a goniometer. The lower body is not constrained during exercise. Therefore, the user can readily and comfortably use this machine.

We verified the effectiveness of this system through squat exercises and analysis of the whole body dynamics. The results showed that this system provides cyclic concentric knee extension exercise.

## 2 DETAILS OF iSAAC

### 2.1 Structure

Figure 1(a) shows an image of the iSAAC. The iSAAC targets the muscles for knee extension based only on concentric power generation. This machine consists of a base unit, an L-shaped slope unit, a sliding board with wheels, various sensors, and an electromagnetic brake. The base unit has two pillars. These pillars support the slope unit at 30°, 45°, or 60°. The L-shaped slope unit has a force plate (Kistler, 9281CA), an electromagnetic brake (Mitsubishi, ZA20Y1), two pulleys, a timing belt, and a rotary encoder. The under pulley is connected through a shaft to the electromagnetic brake and is connected

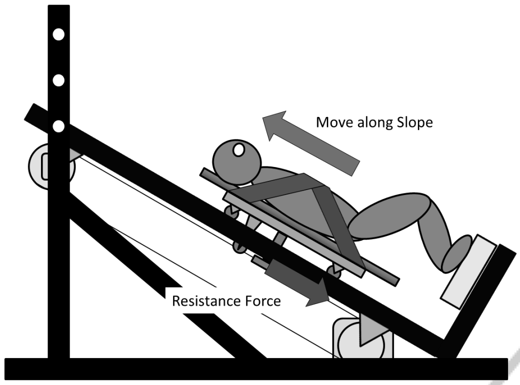



Figure 2: Image of lower extremity training.

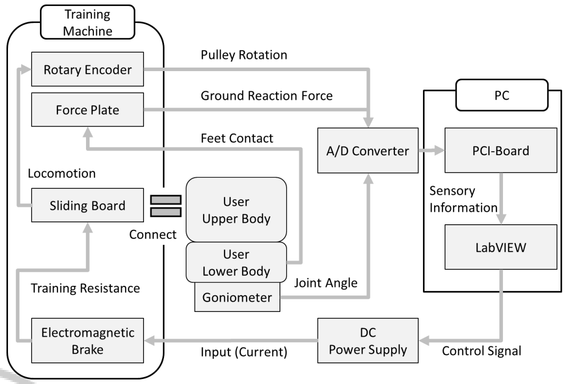



Figure 3: System configuration diagram.

through a timing belt to the upper pulley. The force plate is fixed to the bottom of the slope unit. The slope unit has a pair of rails consisting of two parallel pipes. The sliding board has six wheels, two seat belts, and one connective device. The sliding board is located on these rails and is connected with the timing belt. The user lies on his or her back on the seat, and the user's trunk is fixed on the sliding board by two belts, as shown in Figure. 2. The braking torque from the electromagnetic brake acts as the resistance power when the sliding board slides on the rails.

## 2.2 Actuators

The iSAAC adopts the braking force as training resistance. The merit of using the electromagnetic brake as training resistance is the safety for the human body. The braking resistance acts as a training load while the user lifts up his or her body. The resistance force from the electromagnetic brake is less than or equal to the human-generated force. Therefore, the following relations are satisfied:

$$|F_{EB}| = \begin{cases} |F_H| & (|F_H| < |F_{TL}|) \\ |F_{TL}| & (|F_H| \geq |F_{TL}|) \end{cases} \quad (1)$$

where $F_{EB}$ is the resistance force, $F_H$ is the human-generated force, and $F_{TL}$ is the setup value from the control PC. This is a great advantage because this system automatically regulates the resistance without any delay.

As shown in Figure. 3, the electromagnetic brake is controlled by the input from a DC power supply (Takasago Electric Industry, KX-100L). KX-100L is connected to a control PC by an RS-232C cable with the serial communication method. The control orders for KX-100L are created by LabVIEW (National Instruments, LabVIEW 8.2). We can only control the braking torque generated by the electromagnetic brake. Therefore, this machine has no active power

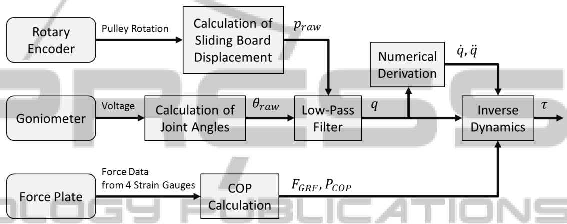
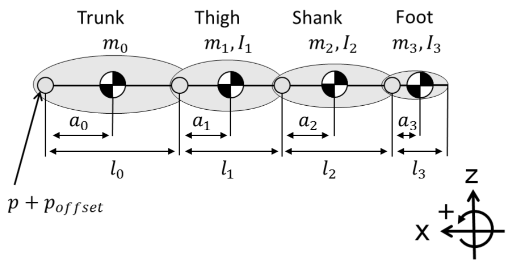



Figure 4: Data flow diagram for dynamics analysis. Two-pass fourth-order Butterworth filter was adopted for smoothing. The cutoff frequency was 12 Hz. The sampling rate of the inverse dynamics was 1 kHz.

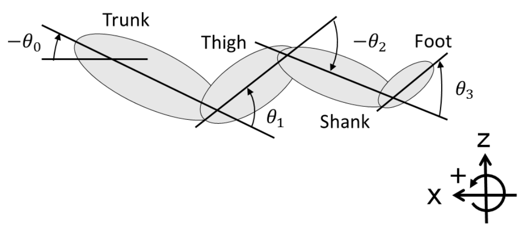
supply device. The rated torque of this electromagnetic brake is 200 Nm. The radius of the pulleys is 0.0980 m. Therefore, the maximum training resistance is about 208 kg.

## 2.3 Sensors

The iSAAC has three sensors. The first sensor is a force plate (Kistler Co., Ltd., 9281CA) located on the bottom of the L-shaped unit and measures the ground reaction force during exercise. The second sensor is a rotary encoder (Koyo Electronics Industries Co., Ltd., TRD-2E1000B) mounted on the shaft end of the upper pulley to measure the locomotion of the sliding board. The last sensor is a goniometer (Biometrics Ltd., SG150) that measures three joint angles (hip, knee, and ankle joints) on the sagittal plane. The angles are relative angles from the proximal segment to the distal segment. The trunk angle is equal to the machine slope. Sensory signals such as the ground reaction forces, pulley rotation, and joint angles are sent to the control PC through A/D boards (DKH, PH701, and PH710) and the PCI board (National Instruments, PCI-6225). All sensor signals are acquired and recorded by the LabVIEW program through the PCI board. The sampling rate of data acquisition is 4 kHz.



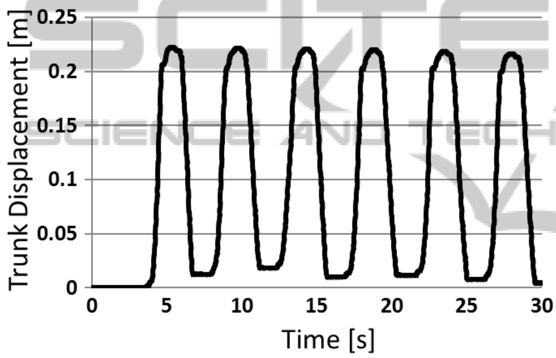

(a) Configuration of physical parameters for segment.



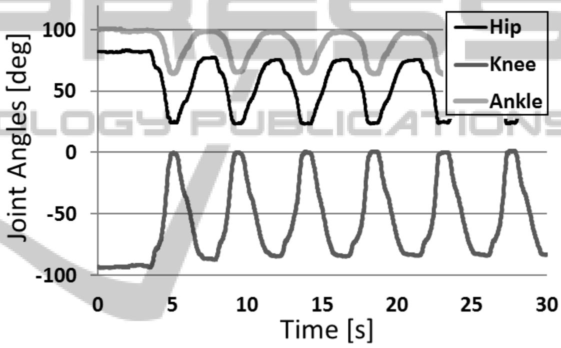

(b) Joint angle configuration.

Figure 5: Four rigid bodies of human model for inverse dynamics analysis. The first segment is the trunk, which includes the head, both arms, and the pelvis. The trunk is fixed to the sliding board. The second segment is the thigh, which is connected to the trunk by the hip joint. The third segment is the shank, which is connected to the thigh by the knee joint. The last segment is the foot, which is connected to the shank by the ankle joint and is in contact with the force plate. $l_i, (i = 0, \cdots, 3)$ are the segment lengths. $a_i, (i = 0, \cdots, 3)$ are the distances from the joint to each segment's center of mass. $m_i, (i = 0, \cdots, 3)$ are the segment masses, and $I_i, (i = 1, \cdots, 3)$ are the segments' inertia moments. The inertia moment of the trunk has no effect on the motion equation (2) because the trunk does not rotate.






(a) Linear behavior of trunk along slope.




(b) Joint angles of lower extremity.

Figure 6: Measured kinetic data during exercise.

## 3 ANALYSIS OF DYNAMICS

We implemented the analysis of dynamics that calculates the joint torque of the lower extremity on the sagittal plane. The analysis system requires sensory information on the motion data and external forces from the environment, as shown in Figure. 4. We assumed that the behavior of the left leg is synchronized with the behavior of the right leg to reduce the number of sensors. Therefore, the human model is represented by four rigid segments, as shown in Figure. 5.

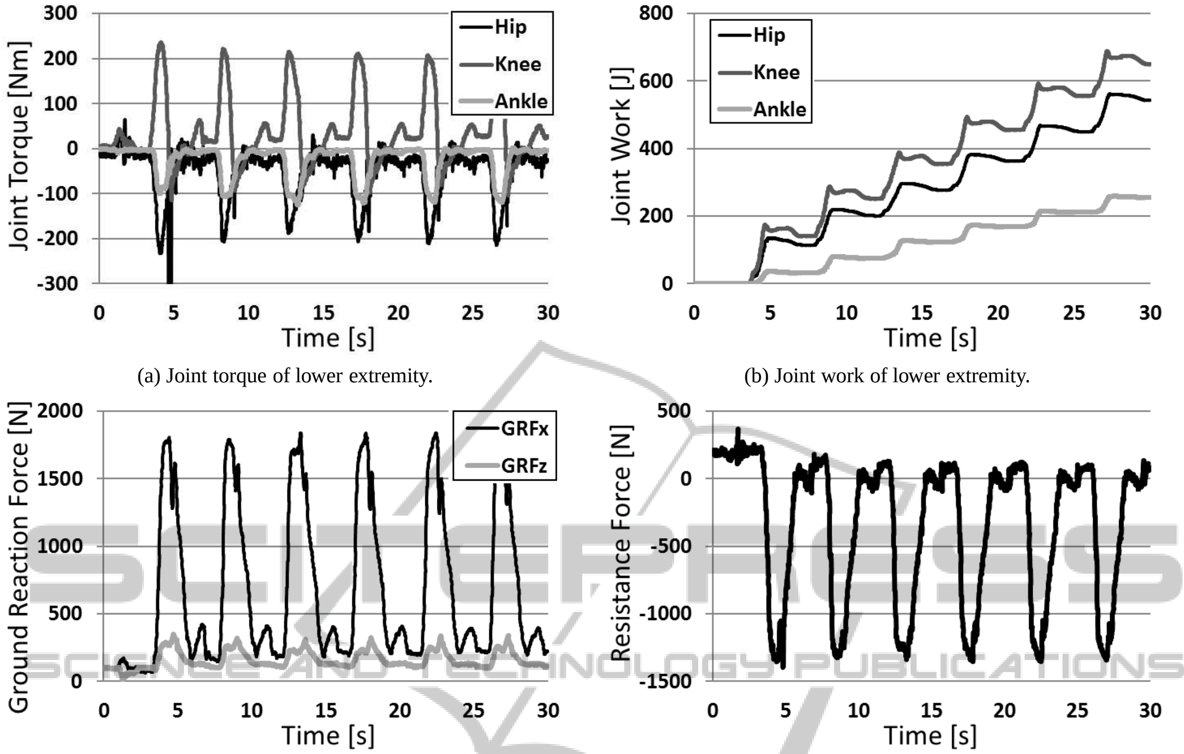
The motion equation of this model is described by

$$M(q)\ddot{q} + h(q,\dot{q}) = S^{\mathrm{T}}\tau + J_R^{\mathrm{T}} F_R + J_{GRF}^{\mathrm{T}}(q) F_{GRF}. \quad (2)$$

where $q = [p + p_{offset}, \theta_1, \theta_2, \theta_3]^{\mathrm{T}} \in \mathbb{R}^4$ is the generalized coordinate vector; $M \in \mathbb{R}^{4\times4}$ is the inertia matrix; and $h \in \mathbb{R}^4$ is the vector that includes the Coriolis force, centrifugal force, and gravity term. $\tau = [\tau_1, \tau_2, \tau_3]^{\mathrm{T}} \in \mathbb{R}^3$ is the joint torque vector, and $S^{\mathrm{T}} \in \mathbb{R}^{4\times3}$ is its Jacobian matrix. $J_R^{\mathrm{T}} F_R \in \mathbb{R}^4$ is the resistance force. $F_R$ is the resistance force in the direction of the slope and includes the effect of gravity on the sliding board. $J_{GRF}^{\mathrm{T}}(q) F_{GRF} \in \mathbb{R}^4$ is the ground reaction force. $F_{GRF} = [F_{GRFx}, F_{GRFz}]^{\mathrm{T}} \in \mathbb{R}^2$ is the total ground reaction forces of both the right and left feet. $p_{offset}$ is the constant offset position of the sternum when the sliding board is located at the lowest (initial) point. $p$ is the displacement of the sliding board and the trunk from $p_{offset}$. $\theta_1, \theta_2, \theta_3$ are the angles of the hip, knee, and ankle joints, respectively.

As shown in Figure. 4, $p, \theta_1, \theta_2, \theta_3$ are calculated based on sensory information. $\dot{q} = [\dot{p}, \dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3]^{\mathrm{T}}$ and $\ddot{q} = [\ddot{p}, \ddot{\theta}_1, \ddot{\theta}_2, \ddot{\theta}_3]^{\mathrm{T}}$ are numerically derived after the filtering process.

Physical parameters such as the inertia moment of the segment are derived from the body weight and segment length from the previous study (Ae et al., 1992); these values are shown in Table 1. The term of the joint torque and the term of the resistance force




(a) Joint torque of lower extremity.

(b) Joint work of lower extremity.

(c) Ground reaction force.

(d) Resistance force.

Figure 7: Analyzed dynamic data of squat-like exercise.



Table 1: Physical parameters of human model.

| Name | Value | Unit |
|---|---|---|
| $M_g$ | 67.000 | $[kg]$ |
| $M_{SB}$ | 27.000 | $[kg]$ |
| $m_0$ | $0.656M_g$ | $[kg]$ |
| $m_1$ | $0.220M_g$ | $[kg]$ |
| $m_2$ | $0.102M_g$ | $[kg]$ |
| $m_3$ | $0.022M_g$ | $[kg]$ |
| $l_0$ | 0.500 | $[m]$ |
| $l_1$ | 0.390 | $[m]$ |
| $l_2$ | 0.390 | $[m]$ |
| $l_3$ | 0.260 | $[m]$ |
| $a_0$ | $0.493l_0$ | $[m]$ |
| $a_1$ | $0.475l_1$ | $[m]$ |
| $a_2$ | $0.405l_2$ | $[m]$ |
| $a_3$ | $0.406l_3$ | $[m]$ |
| $I_1$ | $m_1(0.278l_1)^2$ | $[kgm^2]$ |
| $I_2$ | $m_2(0.274l_2)^2$ | $[kgm^2]$ |
| $I_3$ | $m_3(0.177l_3)^2$ | $[kgm^2]$ |

are normal to each other. Therefore, the joint torque and resistance force are derived as follows:

$$\tau = \left(SS^{\mathrm{T}}\right)^{-1} S\left[M(q)\ddot{q} + h(q,\dot{q}) - J_{GRF}^{\mathrm{T}}(q)F_{GRF}\right] \quad (3)$$

and

$$F_R = \left(J_R J_R^{\mathrm{T}}\right)^{-1} J_R \left[M(q)\ddot{q} + h(q,\dot{q}) - S^{\mathrm{T}}\tau - J_{GRF}^{\mathrm{T}}(q)F_{GRF}\right]. \quad (4)$$

# 4 EXPERIMENTS AND DISCUSSION

In this study, we asked a subjects to perform a cyclic concentric squat-like exercise using the iSAAC to verify the effectiveness of this system. The subject performed squat-like exercises with a constant braking torque. The slope angle $\theta_0$ was 30°. His resistance force of the electromagnetic brake was 115 Nm = 1173 N. This was equal to 70% of one rep max (1RM) for the subject.

The controller of the squat-like exercise was implemented as follows. First, the electromagnetic brake exerted a resistance force when the subject extended his knee ($\theta_2 \leq -10°$). Second, the electromagnetic brake did not operate when the subject extended his knee ($-10° \leq \theta_2$) or bent his knee after knee extension. Finally, the electromagnetic brake again exerted the resistance force when the subject deeply bent his knee ($\theta_2 \leq -80°$) after knee exten-

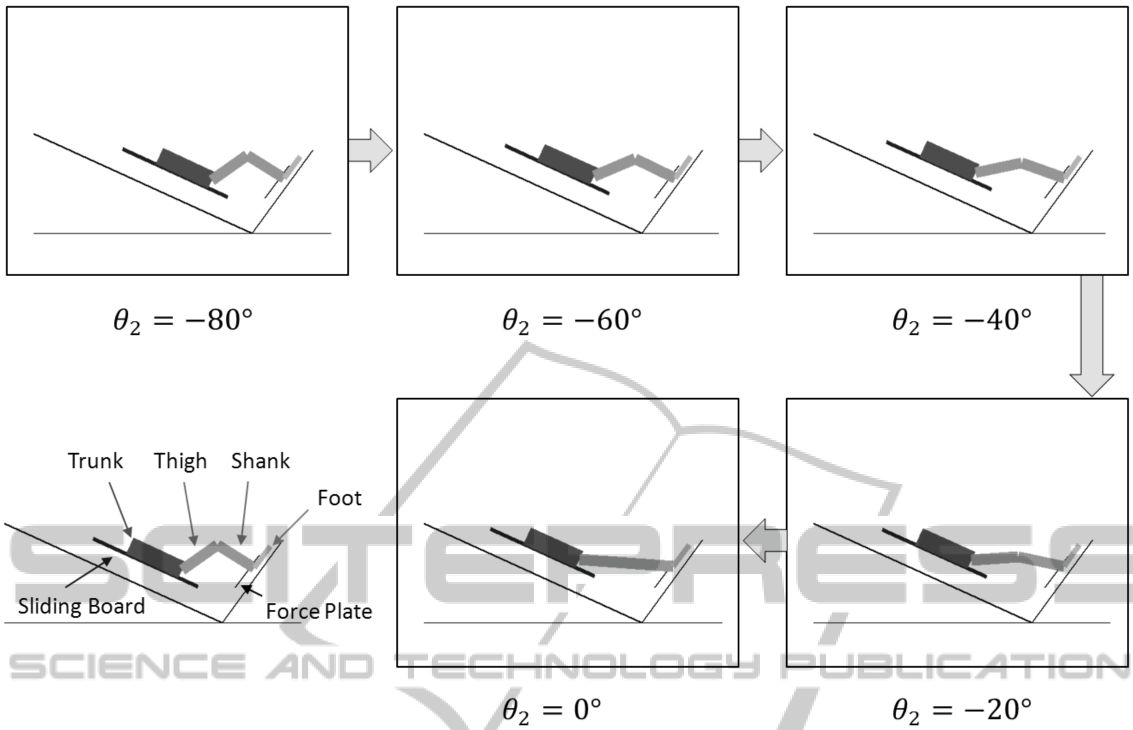



Figure 8: Animation of exercise from sitting position to standing position.



sion. The controller repeated the above three steps.

Figures 6 and 7 show the measured and analyzed data of the squat exercises for the first 30 s. A cyclic concentric exercise was achieved with the iSAAC, as shown in Figure. 6. The resistance force acted as training resistance when the subject extended his knee. In addition, the braking force supported the trunk when the subject sat. The joints exerted the extension torque during the exercise and did positive work, as shown in Figures. 7(a) and (b). Positive joint work means the concentric power generation. Therefore, these results showed that this system lets the user perform safe cyclic concentric training of the knee extension. The resistance force mostly matched the summation of 70% 1RM (1173 N) and the effect of gravity on the sliding board ($M_{SB}g \sin|\theta_0| = 132.3N$), as shown in Figure. 7(d). The system provided the suitable resistance load. Resultant GRF was similar to that of squat exercise (Kellis et al., 2005). Peak knee and ankle joint torque were similar to those of motor controlled leg press (Hahn et al., 2010). Peak hip and ankle joint torque were smaller than those of full squat exercise (80% of 1RM) (Robertson et al., 2008). However, peak knee torque was larger than that of full squat exercise (80% of 1RM) (Robertson et al., 2008). Therefore, the system provided the squat-like knee extension training. In addition, these results show that iSAAC could estimate adequate dynamics. Figure 8 shows the animation of one knee extension movement.

## 5 CONCLUSIONS

In this study, we developed a concentric training machine where the training load is generated by a braking torque. The braking torque acts as concentric training resistance while the user lifts up his or her body. We verified the effectiveness of this machine through squatting exercises and analysis of the inverse dynamics. The results showed that this system provides concentric leg extension exercise. In the future, we will investigate the effects of short- and long-term training programs based on the iSAAC.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