DESIGN AND OPTIMIZATION OF A WHEELCHAIR FOR BASKETBALL USING CAD

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Abstract

During last decades sport activities for disabled people are practiced by many and many athletes, both amateurs and professionals. In order to give the possibility to play safely a variety of sports, the equipments have to be designed with more care than those for able people. Many factors have to be taken into account: athletic performance, safety of both player and opponents, comfort and reliability. For this reason modern computer aided design methodologies seem to be a valid instrument to improve quality of equipments and fulfil the regulations as well. In this paper the authors describe the application of CAD-Multibody techniques to an optimization of a wheelchair for basketball. The target of the investigation is to give to the athlete the possibility to perform quick forward accelerations without rollover tendencies. For this purpose a chair with a self adjustable cushion has been designed. The behaviour of several mechanisms has been virtually simulated and compared: simple pendulum, slider-crank assembly and a combined-multilink. Performances have been assessed simulating the working operation using a virtual dummy embedded into CAD.

Keywords: sport engineering, virtual model.

1. Introduction

During last years the interest for sport activities for disabled people is increased enormously. The causes of this success are due to the organization of dedicated tournament, the improvement of sport equipments and to the attention paid by the media. This positive trend has allowed disabled to play a lot of activities: tennis, rugby, ski, basketball. In order to make easier this practice many equipments have been redesigned, others have been reinvented, others just modified. For these reasons interesting research activity have been started up [1]. The target is to design new devices to improve the performance of the athletes looking at their less abilities, comfort, and respecting the regulations. During last years a lot of international patents have been registered concerning different sport activities for disabled.

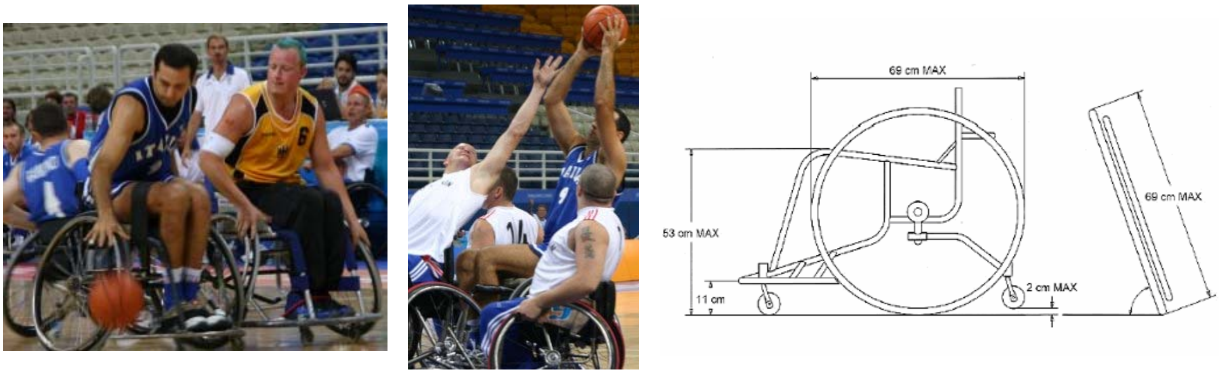

Figure 1: Images from wheelchair basketball match, and main limits imposed by regulations

Among sport activities for disabled, the basketball (or better the wheelchair basketball) is one of the first to be played and at present it is one of the most practiced. All people with upper limb functionality may play this sport. In Europe, the International Wheelchair Basketball Federation (IWBF) indicates a quote of 5160 professional athletes and 500 teams of first and second division. In Italy there are 380 professional athletes who play in 16 teams.

Since there are different kinds of disabilities, international regulations [2] state that each player has to be evaluated by a medical committee that assign him a coefficient of disability (from 1, highly disabled, to 4.5 lowly disabled). The overall coefficient of disability for each team is computed by summing the one of each player of the team and it can not exceed the value of 14. This rule ensures a uniform physical penalty for every team. As concern the wheelchairs the regulations are quite strict. They may have a cushion of maximum 10 cm of thickness (for players with disability coefficient from 1 to 3) or 5 cm (for players with disability coefficient from 3.5 to 4.5). The foot rest can not be placed more than 11 cm above ground level, and it must have a smoothed shape. In order to reduce the risk of rearing, one or two additional wheels (anti-tip device) may be mounted not exceeding the rear wheel silhouette and not exceeding the distance of 2 cm from the ground level. The plane of sitting may not exceed 53 cm (at the highest point) from the ground level. The wheelchair must also have two driving wheels with external rings for propulsion. These rings must have a diameter lower than 69 cm. The wheelchair must not have steering or braking systems or gearboxes.

In order to find out the design target we have to investigate the recently proposed solutions. The first one is described in the U.S. Patent n° 5,851,018 (1988). It is about a wheelchair with rear wheel camber angle which can be adjusted to improve player stability. This feature is obtained with a set of wheel axle different supports which can be easily changed in order to get the desired camber.

A more interesting solution is described in the U.S. Patent 6,161,856 (2000) where the rear axle is mounted by means of a suspension system using a four bar mechanism and a rubber element. When the chair meets an obstacle the suspension system push on the rubber element which dump the dynamic action. This feature improves both comfort and stability.

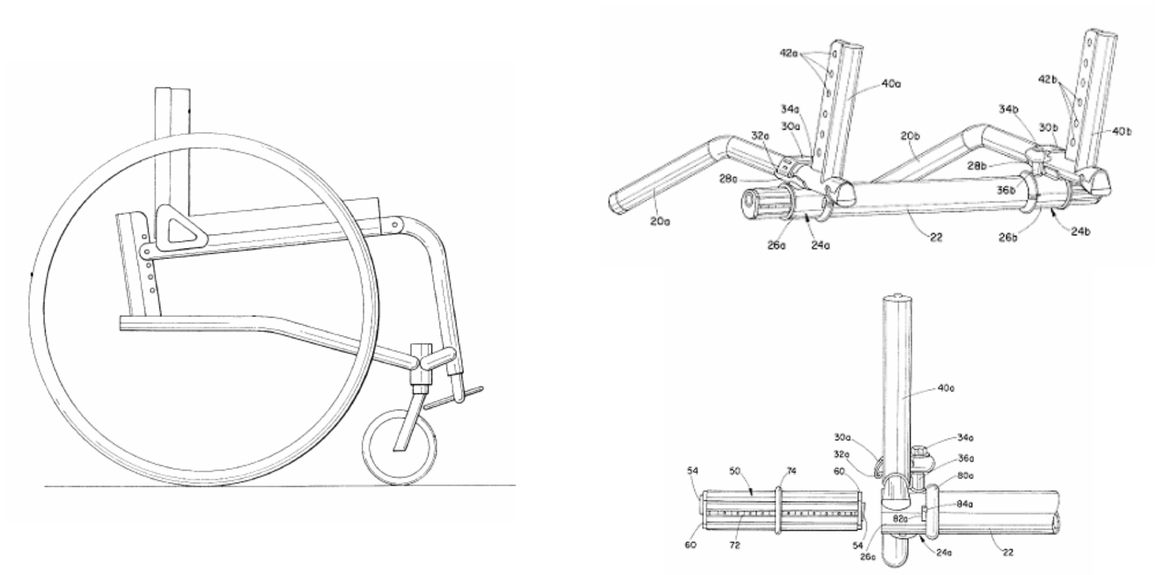

Figure 2: Us Patent 5,851,018: an overall image (on the left) and a detailed view of the camber adjusting system (on the right)

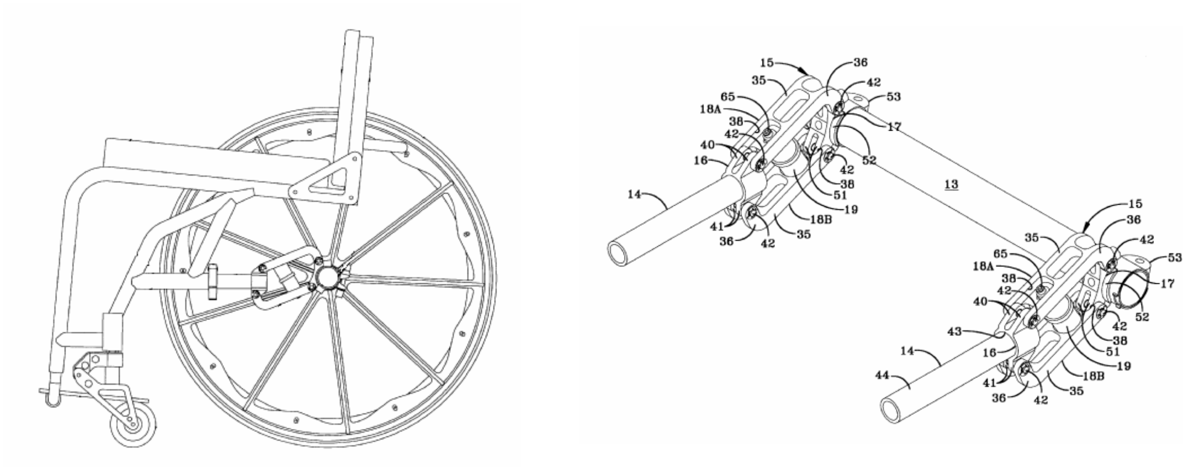

Figure 3: Us Patent 6,161,856: an overall image (on the left) and a detailed view of the four bar mechanism (on the right)

2. Biomechanical interaction between player and wheelchair

Before proposing improvements let us investigate a common wheelchair for basketball. The main components of this equipment are:

- the frame
- the rear axle and the two wheels
- the front wheels
- the footrest
- the backrest
- the anti-tip device

All these components have been modelled into a CAD application referring to actual dimensioning (Figure 4).

In order to simulate the dynamic behaviour of the system the wheelchair has been assembled together with a virtual dummy (anthropometrical data are chosen according to [3] and [4]). The interaction between the dummy and the equipment has been investigated in depth in order to have an accurate assessment about the force exerted by the player and transferred to the equipment, following the approach in [5].

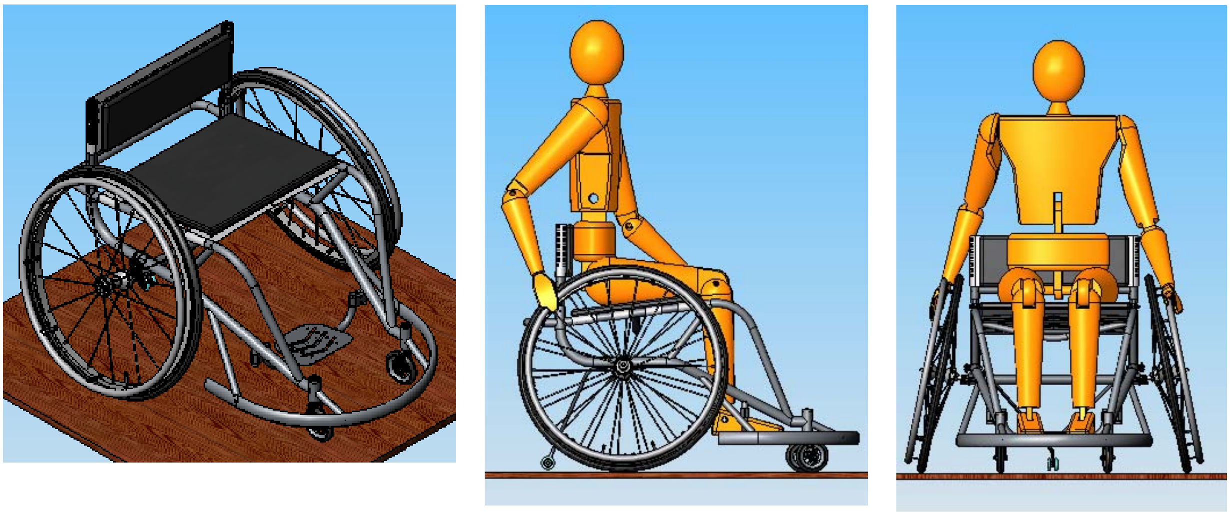

Figure 4: The virtual model of the wheelchair before redesign and the virtual dummy used to simulate player interaction

The dynamic action of propulsion can be split into a tangential force w.r.t. the wheel (which produces the forward movement) and a radial one [6]. Although the radial force is useless, biomechanical studies demonstrated that it can not be avoided in order to allow upper limb ergonomic (and efficient) movements. Let us consider a two dimensional propulsion in the plane of the wheel and neglect the contributions of gravity and inertia. If the propulsion force is applied in the direction from elbow to hand ($\vec{r}_{eh}$) it does not produce work for an elbow rotation (i.e. the moment at elbow is null); if it is applied in the direction from shoulder to hand ($\vec{r}_{sh}$), it does not produce work for a shoulder rotation (i.e. the moment at shoulder is null). Therefore, these directions may be called minimum-effort directions to propulsion of the elbow and shoulder. Both the tangential direction and the minimum-effort directions depend on arm posture, which in the pushing phase is essentially determined by the closed chain of player and wheel. At the beginning of pushing (Figure 5, on the left) the tangential direction clearly deviates from the minimum-effort directions. At the end of the pushing phase (Figure 5, on the right), the minimum-effort and tangential directions make small angles; the mechanical and the physiological requirements can be well satisfied simultaneously.

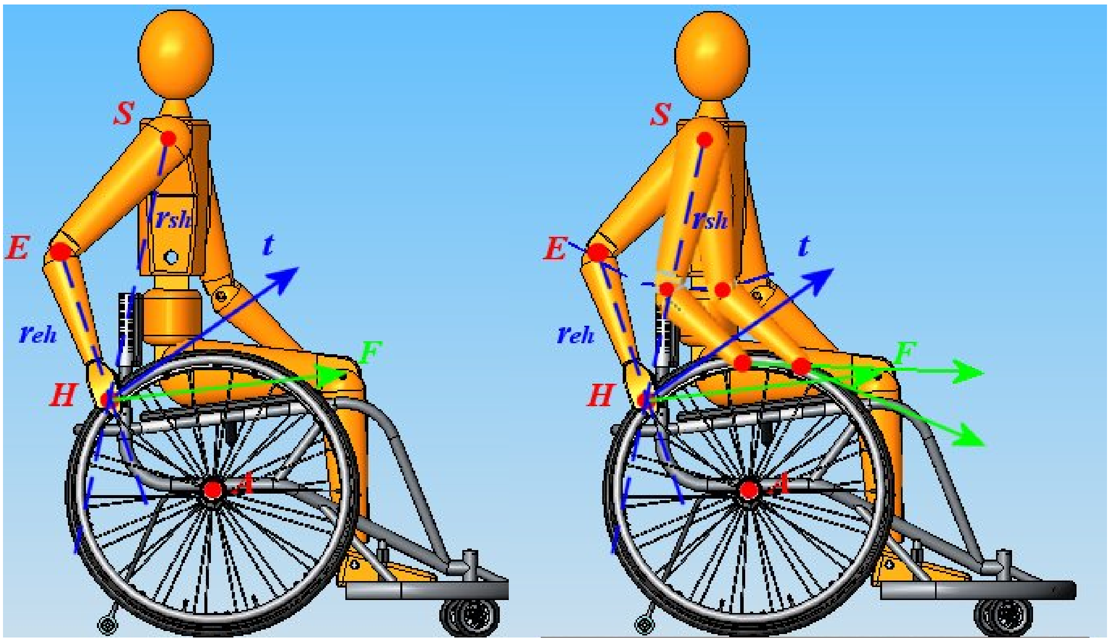

Figure 5. Propulsion kinematics and dynamics

We can define the effect of propulsion *E* as the power of push:

$$E = \left(\vec{r}_{ah} \times \vec{F}\right)\omega \tag{1}$$

where $\vec{r}_{ah}$ is the vector between the hand and the centre of the wheel, $\vec{F}$ is the pushing force and ω is the angular velocity of the wheel.

We can also define the biomechanical metabolic cost function *C* as the level of muscular activity as [7]:

$$C = V_s \frac{\left|\vec{r}_{sh} \times \vec{F} + M_{0s}\right|}{M_{\max s}} + V_e \frac{\left|\vec{r}_{eh} \times \vec{F} + M_{0e}\right|}{M_{\max e}} + C_0 \tag{2}$$

where:

V_s and V_e are the mass of the muscles involved in shoulder and elbow joint movements, respectively;

M_{0s} and M_{0e} are the moments (at the shoulder and at the elbow, respectively) to counteract the gravity and inertia;

$M_{\max s}$ and $M_{\max e}$ are the maximum amplitude (shoulder and elbow) of joint moment depending on angular position and velocity.

C_0 is a baseline of cost value useful for avoiding numerical singularities.

Then we can define the biomechanical yield as the ratio between the effect and the cost:

$$\eta = \frac{E}{C} \tag{3}$$

By maximizing the yield we can obtain the direction of the propulsion force for a desired effort. Experimental tests shows that optimal value of η is about 80%.

In order to solve the problem we have to assess the maximum moments $M_{\max s}$ and $M_{\max e}$. They can be computed as a product of the maximum isometric moment M_{iso}, with an angle factor $f\phi$ [8] and with an angular velocity factor $f\omega$ [9]:

$$\begin{aligned} M_{\max} &= M_{iso} \cdot f\phi \cdot f\omega \\ f\phi &= c_0 + c_1\phi + c_2\phi^2 + c_3\phi^3 \\ f\omega &= \frac{1 - \omega / \omega_{\max}}{1 - \omega / \kappa\omega_{\max}} \end{aligned} \tag{4}$$

Values for evaluating (4) can be found in Table 1.

Table 1: Biomechanical cost function value

	M_{iso} (Nm)	c_0	c_1 [rad^{-1}]	c_2 [rad^{-2}]	c_3 [rad^{-3}]	$\omega_{\max}$ [rad/s]	κ	V [l] [10]
Shoulder extension	79	0.675	0.471	-0.195	0.017	27	0.33	0.36
Shoulder flexion	52	1.138	-0.218	0.073	-0.025	30	0.35	0.32
Elbow extension	43	0.496	0.228	0.215	-0.104	30	0.40	0.17
Elbow flexion	37	0.706	0.302	0.008	-0.053	30	0.45	0.19

Starting from kinematic properties of the propulsion (position, velocity and acceleration of each point) it is possible to maximize the (3), obtaining the direction range of propulsion force. The knowledge of this force allows to assign correct force value in CAD-Multibody model in order to predict the dynamic behaviour.

3. CAD assisted simulation and optimization

The force model proposed in the previous section can be easily integrated in a parametric CAD environment. For this purpose the authors chose Solidworks because it can be used for both modelling and simulating the movement (together with Cosmos-Motion add-in).

The main problem due to propulsion is the wheelchair tendency of rear (yawing) which physically is due to the balancing of angular momentum of the system. The basic idea for optimization is to unlock the seat in order to accomplish the forward movement and reducing the counterbalancing angular momentum transferred from the wheels to the chair. With a self-adjusting seat the centre of mass of the player (and that of the system) can be moved making the forward movement more efficient. Looking at a wheelchair basketball match it is common to see the player moving forward the upper part of his body during forward movement in order to improve stability (avoiding yawing) and acceleration. What we have done is to design a mechanical system to assist and make easier this movement.

In the first proposed solution the seat is connected as a pendulum to the wheelchair frame. Its movement is controlled by a four bar mechanism connected to the bottom part of the seat (Figure 6).

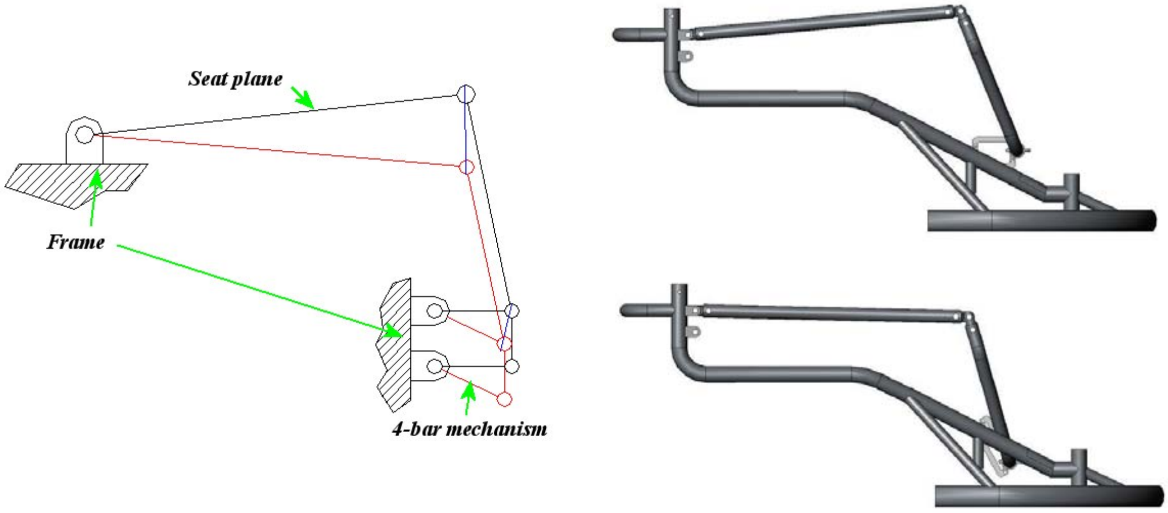

Figure 6: Stick diagram of the first solution (on the left) and CAD model (on the right)

In the second solution the hinge of the pendulum is substituted with a slider in order to make wider the movement of the seating plane during forward acceleration (Figure 7). The solution has one degree-of-freedom more than the previous one, so it requires an accurate suspension system in order to ensure stiffness and stability.

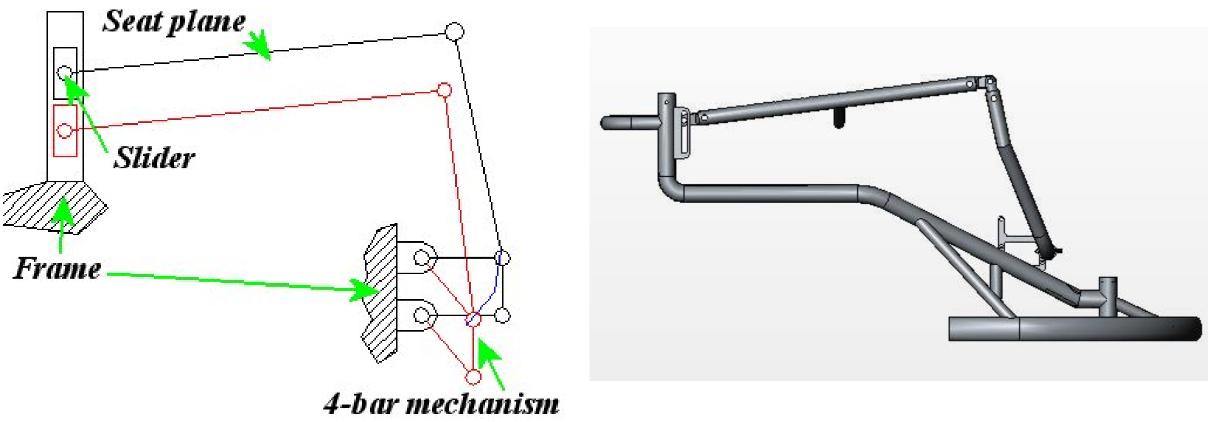

Figure 7: Stick diagram of the second solution (on the left) and CAD model (on the right)

The benefits of the second solution together with a stiffer linkage are obtained in the third solution (Figure 8). The main mechanism for seat plane movement is accompanied by a second multilink linkage which ensure just one degree of freedom and an opportune stiffness. The suspension system is represented by two small spring damper elements in the rear part, hidden under the seat. With this solution the seat undergoes to large displacement with precision thanks to the multilink mechanism.

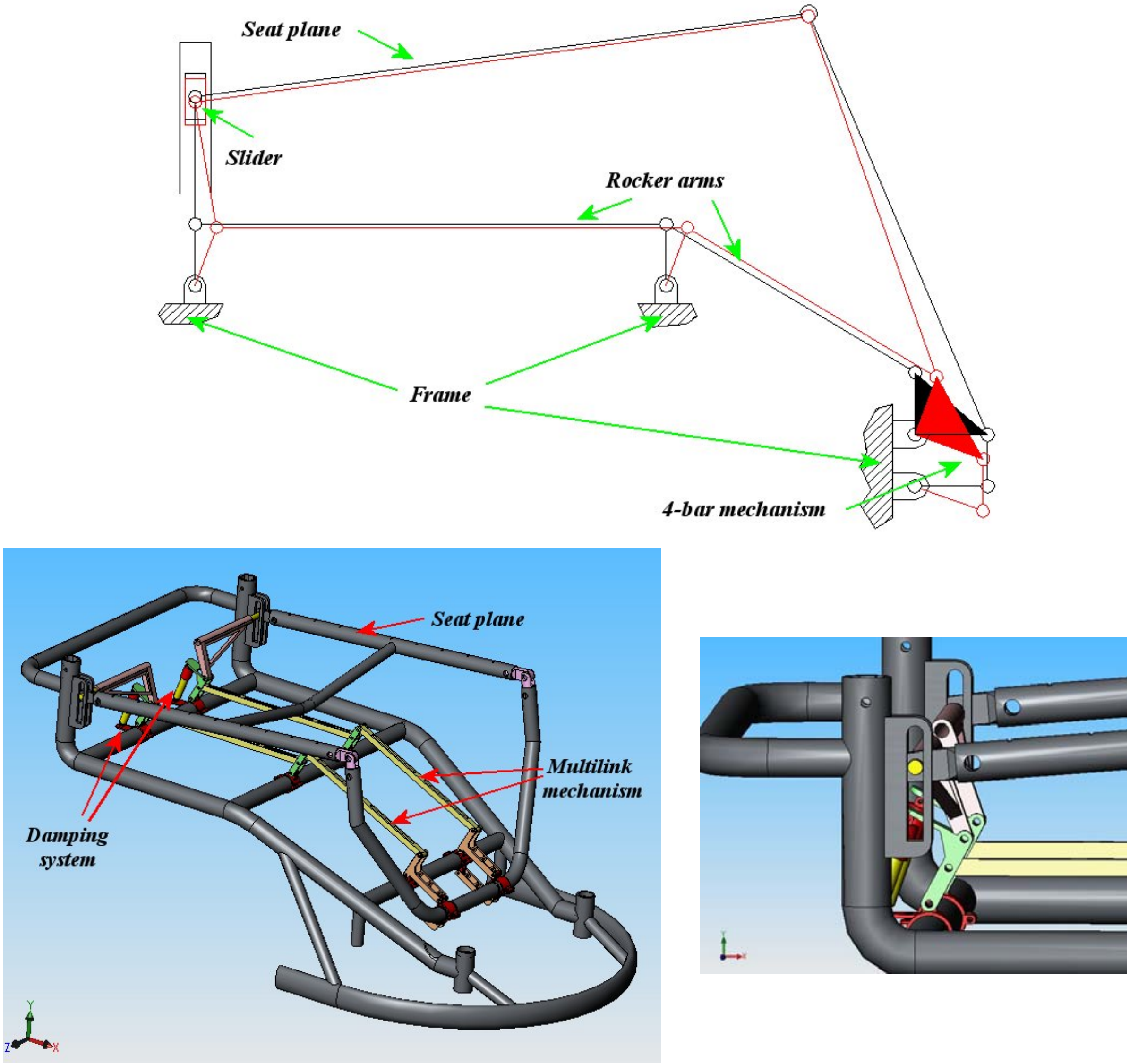

Figure 8: Stick diagram of the third solution (top) and CAD model (bottom) with a detailed view of the suspension system

The dynamic behaviour of the entire system (player + wheelchair) has been investigated and compared for each solution with respect to a traditional chair (with a fixed seat plane). The third solution reveals to be the more efficient. In Figure 9 some result plots are depicted. The main difference is in the vertical displacement of the centre of mass: in the traditional wheelchair the displacement is quite sinusoidal because of the presence of an high yaw velocity. In the modified frame the mechanism damps this effect reducing the centre of mass height and exploiting the potential energy to improve propulsion (Figure 9, at the bottom) and ensure stability. At the same time the system is moved forward without the rebound due to the anti tip system (Figure 9, at the top) which is present in the traditional solution. The period of oscillation and the stiffness of the system may be set choosing appropriate values for damping and stiffness elements of the suspension system. They can be optimized taking into account the weight of the player and his role in the team.

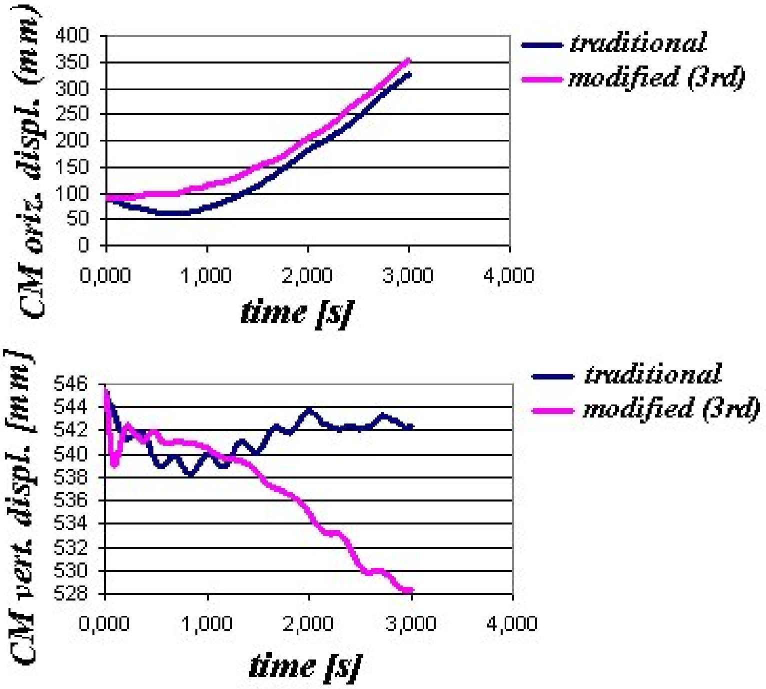

Figure 9: Comparison between dynamic behaviour between standard wheelchair and modified one.

4. Conclusions

It has been proposed a methodology to improve the performance of basketball wheelchair for disabled people. The integration of CAD into standard kinematics and dynamics methodologies allowed to simulate the behaviour of new solutions and to compare them to the standard one in an accurate way using multibody techniques. Moreover a biomechanical model using cost function has been implemented to predict the forces acting between the body and the wheelchair. The investigation started from an understanding of international regulation and an international patents study. The proposed optimized solution has been entirely built and tested into CAD environment. The performed analyses reveal that it allows more stability for the occupant (reducing the risk of rearing and reducing the physical strain during playing) and ensures a quicker forward movement for accelerations.

Acknowledgement

The authors wish to acknowledge Luca Benedetto Vezzaro for preliminary investigation.

References

[1] Cavacece, M., Smarrini, F., Valentini, P.P., Vita, L., "Kinematic and Dynamic Analysis of a Sit-Ski for Improving the Vibrational Comfort" *Sports Engineering* vol. 8 n. 1, 2005, pp. 13-25.

[2] Complete Regulations can be found on the website of *International Wheelchair Basketball Federation*, www.iwbf.org.

[3] Valentini, P.P., Vita, L., "David - A Multibody Virtual Dummy For Vibrational Comfort Analysis Of Car Occupants" *Virtual Nonlinear Multibody System* – NATO Science Series vol.**103** pp. 253-262 – Kluwer Academic Publisher, Holland, 2003.

[4] Pennestrì, E., Valentini, P.P. and Vita, L. ‘Comfort analysis of car occupants: comparison between multibody and finite element models’, *Int. J. Vehicle Systems Modelling and Testing*, (2005) Vol. 1, Nos. 1/2/3, pp.68–78.

[5] Richter, W.M. The effect of seat position on manual wheelchair propulsion on biomechanics: a quasi-static model-based approach. *Medical Engineering & Physics* 23 (2001) 707–712.

[6] Zoendaal, L.A., Veeger, H.E.J., Van der Woude, L.H.V. The push force pattern in manual wheelchair propulsion as a balance between cost and effect. *Journal of Biomechanics*, 36 (2003) 239–247.

[7] Happee, R., *The control of shoulder muscles during goal directed movements*. Ph.D. thesis, Delft University of Technology, The Netherlands, 1992. (Appendix C: Criteria for the load sharing problem).

[8] Kulig, K., Andrews, J.G., Hay, J.G., Human strength curves. *Exercise and Sport Sciences Reviews* 12, 1984, 417–466.

[9] Davis, G.M., Shephard, R.J., Strength training for wheelchair users. *British Journal of Sports Medicine* 24, 25–30, 1990.

[10] Veeger, H.E.J., van der Helm, F.C.T., van der Woude, L.H.V., Pronk, G.M., Rozendal, R.H., Inertia and muscle contraction parameters for the musculoskeletal modelling of the shoulder mechanism. *Journal of Biomechanics* 24, 1991, 615–629.