Applied Collegiate Exoskeleton Competition Rulebook

Version 3.03

Table of Contents

Article I. Major Changes Made

1) Required safety reports from competing teams
2) The focus of this competition this year is on strength and endurance augmentation and is reflected in scoring
3) Development of Safety Review Committee

Article II. Executive Overview

Section 1.01 ACE Competition Statement:

The ACE Competition is a cross-university competition aimed at testing the functional capabilities of exoskeletons designed and built by their respective universities. The purpose of this is to help push forward and increase interest in this relatively new and upcoming technology of exoskeletons by creating a friendly competition where teams can test the actual real-world potential of their designs. To realize this goal, the competition is designed around elements of the Candidate Physical Ability Test (CPAT), which assesses the physical ability of entry-level firefighters. This provides a reliable test of real-world physical tasks in which a powered exoskeleton would likely encounter.

All teams are expected to behave in a fair and constructive way and not take advantage of rule loopholes. The organizers of the ACE Competition reserve the right to alter the rules if deemed necessary.

Section 1.02 Competition Design

The competition itself is split into two sections: ridged exoskeleton and soft exoskeleton. Each team will submit their section choice with their safety report two weeks in advance of the competition. Definitions of exoskeleton types is in Table 2 of Appendix A.

Each section will go through a design review, obstacle course, and a endurance test. These three parts of the competition are designed to measure the exoskeleton's performance in the tasks necessary to a real-world scenario for a rescue worker. Each part of the competition is outlined in Article 5 and the scoring is outlined in Appendix A table 3 and 4.

Section 1.03 Brief Technical Summary

1) Exoskeleton suit must be portable stand-alone device and it cannot be tethered to a power source that is located off of the suit.
2) Exoskeleton suit must be designed to passively or actively assist the user in movement or transfer loads off the user to the ground.
3) No unauthorized power sources (see article 3.04 for more information).
4) Exosuit must be controlled by the user, no outside control may be utilized.
5) Exoskeletons must pass safety inspection in order to compete in ACE.
6) Documentation relating to the exoskeleton must be submitted prior to the competition.
7) Exoskeleton parts cannot poise potential harm to user or bystanders.

Article II. Documentation Requirements

All reports will only be viewed by ACE safety review committee.

Section 2.01 Title Page

Section 2.02 Acknowledgements

Section 2.03 Cover Sheet

1) Background on team
   a) Project Goals
   b) Exoskeleton type, power source, and actuation method
2) Table of contents

Section 2.04 Mechanical Overview

1) Picture/Diagrams of exoskeleton suit
2) Structure overview
3) How it meets safety requirements

Section 2.05 Electrical Overview

1) Block Diagram of Electrical system with voltage lines labeled
2) Power system overview
3) Actuation overview
4) User input detail
5) How it meets safety requirements

Section 2.06 Software Overview

1) Control system detail

Section 2.07 Safety Concerns for Suit

Section 2.08 References

Section 2.09 Appendix

Article III. Technical Requirements

Section 3.01 Actuation

1) Non-passive exoskeletons (i.e. active actuation) must have an emergency shutoff switch that is accessible no matter the orientation of the exoskeletons.
2) Pneumatic systems must be able to release pressure with an emergency shut off.

Section 3.02 Mechanical Specifications

1) Exosuit must have mechanical stops preventing any joint movements beyond the physical limits of the user. Follow the joint limitation guidelines in Appendix A, Figure A.
2) Mechanical joints must be capable of handling above the expected forces it will be under. Teams must provide calculations or finite element analysis showing that the exoskeleton's joints are capable of handling the forces they will experience without being compromised.

3) Physical stops must be used to prevent joints from going beyond users range of motion.
4) Suit must have tether hook that will be able to withstand the combined weight of the user, exoskeleton, and load.
5) Pilots will have a provided rolling gantry frame with the tether to be secured to the exoskeleton's tether hook.

Section 3.03 Electronics

1) Electronics cannot be grounded to the suit (no connection between electronics and body of the suit).
2) No loose wires on suit, tripping hazard. Must attached to exoskeleton's structure.

Section 3.04 Power Specifications

1) Exosuit cannot use flammable liquids or gas for fuel with the exception of LiPo batteries.
   a) This does limit the power sources that can be used. It would make sense to use something like a small gas engine due to the high energy density of gasoline, but exoskeletons are dangerous enough without the potential to spontaneously explode in flames.
   b) Specifications on the allowable use of LiPo batteries are in the LiPo battery section at the end of the safety rules
2) LiPo Battery Specification Summary:
   a) Purchasing and Application
      i) The Lithium-ion Polymer (LiPo) battery should only be purchased as a battery pack, and not as individual cells.
      ii) The battery pack cannot be modified at any level
         1. Wires (main charge/discharge lead and balancing lead) cannot be cut.
         2. Internal cells cannot be removed.
         3. The embedded Protection Circuit Module (PCM) cannot be modified.
      iii) Only original LiPo battery packs can be purchased with proper manufacturer and fabrication/expiration date information.
      iv) The Robotic Exoskeleton Suit must have a quick removal system that unlocks the LiPo battery container in case of emergency and can be removed in 30 seconds.
   b) Damage Protection
      i) A hard case and fire-resistant container should be attached to the Robotic Exoskeleton Suit in order to hold the LiPo battery pack.
      ii) The container cannot be airtight (risk of building internal pressure). If the purchased container is completely sealed, a hole should be drilled on its top surface to allow air flow.
      iii) The container must be one of the following options:
         1. Fireproof safe bag
         2. Metal ammo case

3. Fire safe box

c) Charging and Storing LiPo Batteries

i) When not in use the LiPo batteries should be stored inside the required containers.

ii) Only standard connectors should be used to plug the battery to the load/power distribution system (shown below in Table 1).

Table 1: Suggested Battery Connectors

Anderson Power Poles	EC3 Connectors	Deans Connectors
Molex connectors	Traxxas Connectors	XT-60 Connectors

iii) A LiPo compatible charging system recommended by the battery pack manufacturer should be used.

iv) All LiPo battery packs should always be charged using the procedures described in Section 2.2(A).

d) Emergency Removal System

i) The robotic exoskeleton suit must have a quick removal system that unlocks the LiPo battery container in case of emergency (combustion).

ii) The wearer should have complete control of the locking/unlocking system and be able to remove it in under 45 seconds.

iii) During container release/ejection, the battery should be unplugged by either triggering an auto wire cutting feature (positive and negative wires separately), or by releasing a longer wire (battery pack is displaced away from the wearer).

Article IV. Safety Inspection

Section 4.01 Safety Report Analysis

1) Reports submitted by each team will be analyzed for improper safety precautions. Teams in violation will be notified no later than one week prior to competition to make necessary changes and to re-submit report to safety committee.

Section 4.02 Participant Requirements

1) The exoskeleton user must wear a helmet and safety glasses while participating in the competition.

Article V. Design Review

The design review is focused on testing such elements of the exoskeleton such as safety, don/doff time, cost, and design choices. The review is conducted by a panel of judges and all student teams. The (tentative) scoring metric can be found in Appendix A, table 3.

Section 5.01 Judges Panel

1) The panel will be consisting of either professors, people in industry, or both. Additionally, all student teams competing will conduct a design review of their peers. The reviews from each student team will be made available to panelists to further their assessment of each exoskeleton.

Section 5.02 Don/ Doff Test

1) The don/doff test is designed to test how quickly a user can put on the suit, and how fast they can remove it in an emergency situation.
2) These metrics are important for two reasons: when a rescue worker is called to an emergency, they must be able to suit themselves into the gear they need as quickly as possible.
3) A faster don time means a quicker response time to the emergency.
4) In the event that the suit becomes a danger to the participant, the suit must be able to be removed as quickly as possible.

Section 5.03 Cost Analysis

Article VI. Scoring Guidelines

Teams entering the competition will select to have their exoskeleton classified as a ridged exoskeleton or a soft exoskeleton. Each exoskeleton type will complete a design review, obstacle course, and an endurance test. The only difference between the two exoskeleton types is the ridged exoskeleton will focus more on strength augmentation by carrying two 25-pound weights where the soft exoskeleton carries one 25-pound weight. All Tables for Scoring is in Appendix A.

Section 6.01 Obstacle Course Design

CAD versions of each obstacle will be added within the next three weeks. Also still deciding if we will be using stepping stones or uneven terrain.

1) Stair Test
    a) The pilot must climb up and down a set of stairs with handrails which helps assess the basic movement capabilities of the exoskeleton.

2) Stepping stones
    a) Pilot must step on a marked path, one foot per spot (ie. you step on the first spot with your left foot, the second with your right, the third with your left, etc.). The spots will be marked on the ground.
    b) At least one foot must be on the ground at all times, so no jumping.

c) Points deducted for misstep (i.e., for not landing your foot in the marked zone or for putting both feet in one zone).

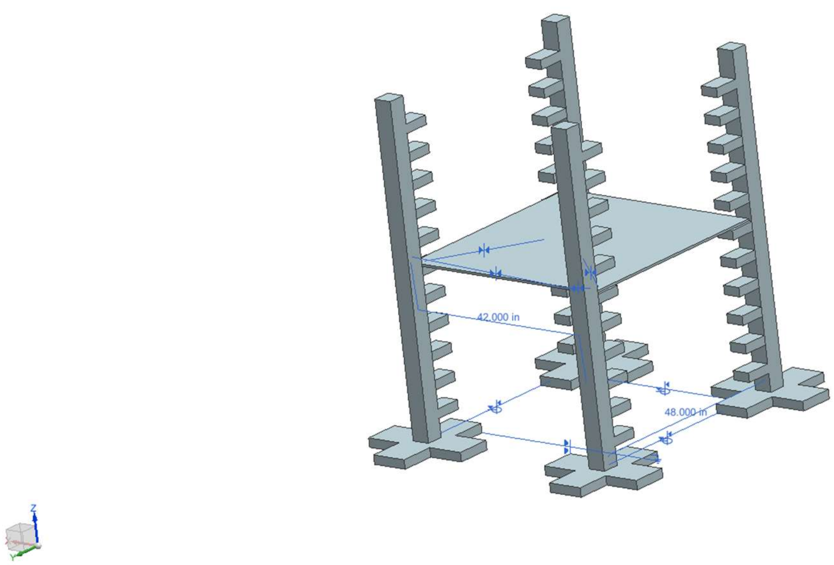
d) Testing hip flexibility, but in more directions. Also testing how much the exosuit resists the pilot spreading their legs.

3) Uneven Terrain

a) In any rescue work the likelihood that the pilot will walk over strictly even terrain is very low. This will assess the exoskeletons ability to be functional in any sort of unpredictable or uneven terrain. Due to the need for hard objects such as cinder blocks and loose wood, the suit must be attached to a rolling gantry frame for this section of the competition to prevent injury in the case of a fall.

4) Crouch Test

a) The pilot will need to crouch and walk under a platform set before the start at approximately 2/3rds the height of the pilot. This test assesses the exoskeletons ability to duck through collapsed areas without locking up, and any other situation involving crouching such as to pick up and carry a fallen individual.

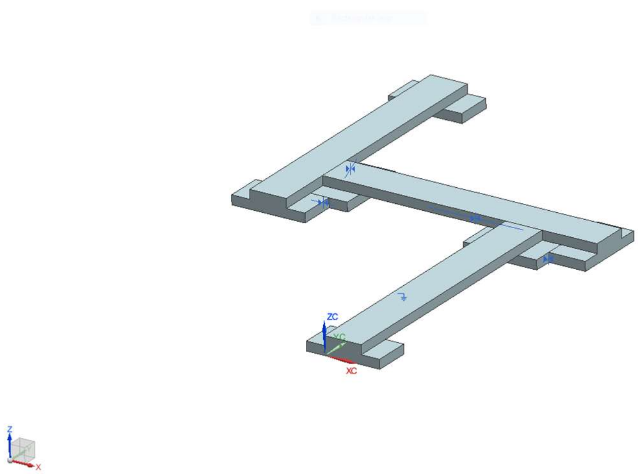


5) Balance Beam

a) A straight beam, ~1 ft in width, not very high off the ground

b) Pilot must be able to walk across the entire beam without falling, or else they will have to start at the beginning of the trial.
There are two trials:
1. Must walk one foot in front of the other (ie. normal walking)
2. Must shuffle sideways, without crossing feet (uncomfortable squatting not necessary).

c) Testing hip flexibility and balance



Each test will be timed separately. At the beginning of each section, a timer will start allowing them to proceed through the obstacle. Upon completion of the section (by reaching a designated area on the other side) the timer will be stopped. From a safety perspective, this is necessary to allow the pilot time to assess any issues arising with their suit before starting the next obstacle, as well as allowing time to attach the tether for the balance and uneven terrain sections.

Section 6.02 Motion Capture Analysis

1) Purpose is to look at users range of motion, does not need any modification to suit.
2) Each person will walk in front of a camera with and without the exoskeleton, this is to see how natural the motion is with the exoskeleton on.
3) Due to this being the first year this test is being conducted, not very many points will be assigned to this obstacle.

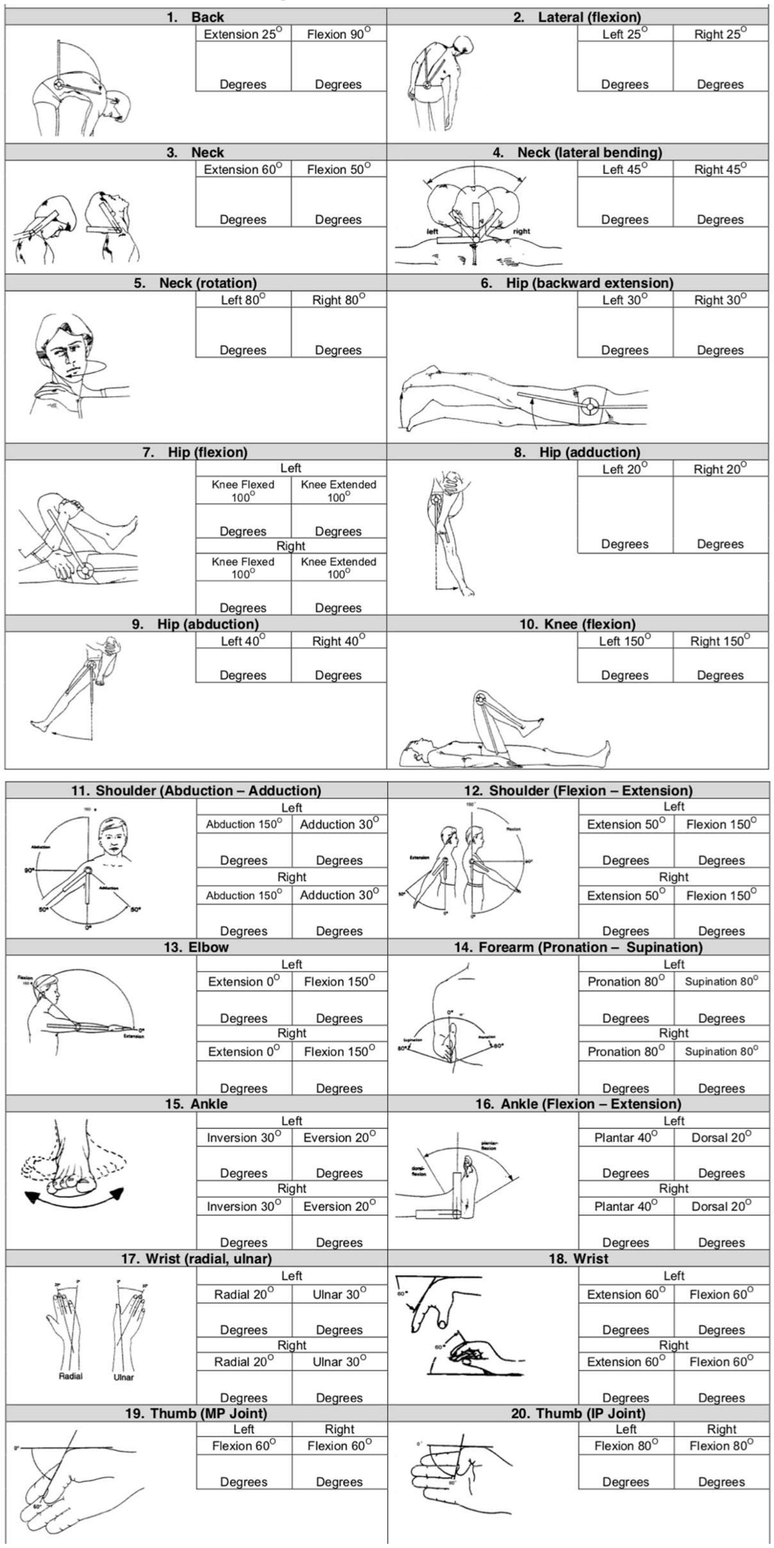
Section 6.03 Efficiency Test

This test is designed to see if the exoskeleton is, in fact, reducing the mechanical energy expenditure of the user. For this test, one pilot will be loaded in four different conditions:

without exoskeleton/without weight
without exoskeleton/with weight
with exoskeleton/without weight
with exoskeleton/with weight

It will be the same weight that is used in the obstacle course portion of the competition. The pilot will proceed to walk on a track for five minutes under each condition while equipped with a metabolic tester that measures gas exchange during respiration. To account for individual differences, the difference in VO2 will be used as the scoring metric. The first difference will be (VO2 with exoskeleton suit, no weight - VO2 without exoskeleton suit, no weight) and the second difference will be (VO2with exoskeleton suit, weighted - VO2 without exoskeleton suit, weighted). Points will be awarded relative to the other teams, where the lowest VO2 differentials will get the most points.

Appendix A. Tables and Figures



1. Back

Extension 25°	Flexion 90°
Degrees	Degrees

2. Lateral (flexion)

Left 25°	Right 25°
Degrees	Degrees

3. Neck

Extension 60°	Flexion 50°
Degrees	Degrees

4. Neck (lateral bending)

Left 45°	Right 45°
Degrees	Degrees

5. Neck (rotation)

Left 80°	Right 80°
Degrees	Degrees

6. Hip (backward extension)

Left 30°	Right 30°
Degrees	Degrees

7. Hip (flexion)

Left	
Knee Flexed 100°	Knee Extended 100°
Degrees	Degrees
Right	
Knee Flexed 100°	Knee Extended 100°
Degrees	Degrees

8. Hip (adduction)

Left 20°	Right 20°
Degrees	Degrees

9. Hip (abduction)

Left 40°	Right 40°
Degrees	Degrees

10. Knee (flexion)

Left 150°	Right 150°
Degrees	Degrees

11. Shoulder (Abduction – Adduction)

Left	
Abduction 150°	Adduction 30°
Degrees	Degrees
Right	
Abduction 150°	Adduction 30°
Degrees	Degrees

12. Shoulder (Flexion – Extension)

Left	
Extension 50°	Flexion 150°
Degrees	Degrees
Right	
Extension 50°	Flexion 150°
Degrees	Degrees

13. Elbow

Left	
Extension 0°	Flexion 150°
Degrees	Degrees
Right	
Extension 0°	Flexion 150°
Degrees	Degrees

14. Forearm (Pronation – Supination)

Left	
Pronation 80°	Supination 80°
Degrees	Degrees
Right	
Pronation 80°	Supination 80°
Degrees	Degrees

15. Ankle

Left	
Inversion 30°	Eversion 20°
Degrees	Degrees
Right	
Inversion 30°	Eversion 20°
Degrees	Degrees

16. Ankle (Flexion – Extension)

Left	
Plantar 40°	Dorsal 20°
Degrees	Degrees
Right	
Plantar 40°	Dorsal 20°
Degrees	Degrees

17. Wrist (radial, ulnar)

Left	
Radial 20°	Ulnar 30°
Degrees	Degrees
Right	
Radial 20°	Ulnar 30°
Degrees	Degrees

18. Wrist

Left	
Extension 60°	Flexion 60°
Degrees	Degrees
Right	
Extension 60°	Flexion 60°
Degrees	Degrees

19. Thumb (MP Joint)

Left	Right
Flexion 60°	Flexion 60°
Degrees	Degrees

20. Thumb (IP Joint)

Left	Right
Flexion 80°	Flexion 80°
Degrees	Degrees

Figure A: Range of Joint Motion

Table 2: Exoskeleton Type Definition

Exoskeleton Type:	Definition:
Ridged Exoskeleton	Majority of added weight is displaced through suit.
Soft Exoskeleton	Majority of added Weight is displaced through user.

Table 3: ACE Competition Judging Score Breakdown

Design Judging Score Sheet		Team Name:
Category	**Description**	**Possible Score**
Exoskeleton Design	This category looks at the structural design of the exoskeleton frame. Teams should demonstrate a thorough attention to design factors in their development of the frame, including but not limited to: 1. Does the range of motion of the frame allow for the pilot's natural movements? 2. Do components of the frame jut out in ways that can easily catch or collide with objects in the pilot's environment? 3. Is the selection of materials appropriate for its application in the frame?	70
Method of Actuation	This category looks at the methods with which the exoskeleton assists the pilot. This includes passive and active elements which either add power to the pilot's movements or transfers loads off the pilot.	70
	Areas to consider include:	
	What is the justification behind each joint's actuation type?	
	Is the actuation loud to the point of hindering verbal communication?	
	Does the size of the actuation hinder the pilot's range of motion?	
	Does the size of the actuation greatly increase the chance of hitting obstacles?	
Attachment	This category focuses on the method of attaching the exoskeleton to the pilot's body.	30
	Areas to consider include:	
	Does the suit optimize the number of attachment points needed?	

	Do the attachment points appear to put uncomfortable pressure on the pilot?	
	Does the suit allow for a wide range of adjustment to match the pilot's physical dimensions?	
	Are the attachment points easily accessible to the pilot?	
	Do the attachment points add unnecessary bulk to the suit?	
	Do the attachment points have a quick and simple system for connecting and disconnecting?	
Safety	This category focuses on the suit's overall safety for the pilot wearing it.	30
	Areas to consider include:	
	Do actuated joints have mechanical stops preventing movements beyond the physical range of a healthy human?	
	(If using electronic control) Does the suit have electrical/software stops to prevent actuation past the physical range of a healthy human?	
	When unpowered, is the pilot able to still move in the suit?	
	Are there calculations showing the actuated joints can handle peak forces? If using a LiPo battery, can the wearer remove it in under 45 seconds?	
	Total:	200

Table 4: Dynamic Course Judging Score Sheet

Dynamic Course Judging Score Sheet			
Test		**Score Calculations:**	**Scoring**
Don/Doff	This test consists of two parts (No weight attached during this portion). 1. 3 people must don and doff the suit completely. When the first person has taken off the suit, the next person may begin to put on the suit. This can all be done with the help of other team members. Time starts when the first pilot begins donning the suit, and time is stopped when the third pilot has completely taken off the suit.	Max 25 points per test. 2 trials per test. 1st = 25 pts, 2nd = 20 pts, 3rd = 15 pts, 4th = 10 pts, 5th = 5 pts	50

	2. The second part of the test is an emergency doff. This test starts with a pilot in a fully secured suit, when time is started, the pilot must doff the suit without the help of teammates. Time stops when the pilot has completely removed the suit. The suit must have an attachment point for a harness which will be clipped to an overhanging support frame with approximately 3" of slack in the harness. This is to allow the pilot to focus entirely on escaping the suit without worrying about dropping the suit onto the ground and damaging it.		
Obstacle Course	Section 1: peg wall/vault and crouch Section 2: weight carry/balance beam Section 3: stepping stones/ramp	Max 100 points per pilot. Fastest pilots compared to each other. Second fastest pilots compared to each other. Third fastest pilots compared to each other. 1st = 300 pts, 2nd = 80 pts, 3rd = 60 pts, 4th = 40 pts, 5th = 20 pts 50% point reduction for not using weight	300
Efficiency	6 min walking without exoskeleton with 30 pounds 6 min walking with exoskeleton with 30 pounds (only second half of data used)	1st = 225 pts, 2nd = 200 pts, 3rd = 175 pts, 4th = 150 pts, 5th = 125 pts 50% point reduction for not using weight	225

Motion Capture	Walk in front of video camera with and without suit	1st = 25 2nd = 20 3rd = 15 4th = 10 5th = 5	25
		Total	600

Appendix B. Committee Guidelines

1. Safety Committee

a) Committee is made of one representative from all schools participating in ACE competitions for at least 2 years.

b) Responsible for ensuring the safety of the competition and design of ACE competition rules.

Appendix C. Power

1. LiPo BATTERY OPERATION GUIDELINES

a) Important Considerations

i) While the use of LiPo batteries in many devices is practical and desirable, there are certain dangers associated with their use. It is important to follow these instructions to limit those dangers. LiPo batteries store a large amount of energy and should be treated with extreme caution. Additionally, it has been determined that LiPo batteries, when not properly used, may burst and catch fire. Failure to comply with these instructions will void the battery warranties and may result in property damage, personal injury, and/or loss of life.

b) Charging

i) LiPo batteries should always be charged using LiPo compatible chargers. This kind of batteries are charged using a system called CC/CV charging, which stands for Constant Current / Constant Voltage. In this method, the charger will keep the current (charging rate) constant until the battery reaches its peak voltage. Then, it will maintain that voltage, while reducing the current. A different method is used for NiMH and NiCd batteries, a pulse charging process. This charging method could cause damaging effects to LiPo batteries, hence the importance to have a LiPo compatible charger. In addition, another reason for using LiPo compatible chargers is for balancing, which is the process of equalizing the voltage of each cell in a battery pack. When a LiPo battery is balanced, it is ensured that each cell will discharge the same amount during operation. This is crucial for maintaining the battery performance, while providing a safe usage. The safest charge rate for most LiPo batteries is one times (1x) the capacity of battery in Amperes (i.e. for a 3000mAh battery, charge rate = 3A). Another safety precaution is to charge the LiPo battery inside a fireproof safe bag.

c) LiPo battery charging tips:
    i) Always check if the settings for the LiPo charger are matching the battery pack characteristics (i.e. cell count, current settings, etc.).
    ii) Always check the battery connectors orientation. Reverse charging can lead to cell damage, fire or explosion.
    iii) Always charge LiPo batteries on fire-resistant surfaces (i.e. cement, steel, ceramic, etc.).
    iv) Do not charge LiPo battery packs near flammable products or liquids.
    v) Do not charge LiPo battery packs while inside another electronic device.
    vi) LiPo battery packs should be charged within a temperature range of 0°C to 50°C.
    vii) Never leave a charging LiPo battery pack unattended.
    viii) Never charge a LiPo battery pack that has ballooned or swelled due to overcharging.
    ix) Never charge a LiPo battery pack that has been punctured or damaged in a crash.
    x) Have a fire extinguisher near the charging area or a large bucket of dry sand. Do not use water in case of fire.
    xi) If the LiPo battery pack starts to swell, stop the charging process immediately.

d) Discharging
    i) Before using the LiPo battery pack, check if the cell voltage after the first charge has not exceeded the range specified for its type (1S, 2S, 3S, etc.). Verify the voltage of each cell via the balance connector and make sure that each cell is between 4.15V and 4.22V (peak voltage). The LiPo battery pack should be discharged at a temperature range between 0°C and 50°C. If the LiPo battery exceeds 70°C during discharging or handling, it may be damaged and catch fire. It is also recommended to use low current during the first discharge and divide the discharge time into 6-minute sessions with 15-minute breaks in between. Never discharge the battery at a higher current than the maximum continuous discharging current specified in the LiPo battery pack label. A higher discharging current may cause overheating which will lead to ballooning, swelling, or possibly result in fire (i.e. for a 5000mAh 35C battery, discharge current < 175A). In addition, for a longer life cycle, a continuous discharging current of 70%-80% of the designed maximum discharging current is recommended. Caution must be taken in order to not discharge a LiPo battery pack below the lowest discharge voltage. This may cause irreversible damage which will deteriorate battery performance and life cycle.

e) LiPo battery discharging tips:
    i) A one-cell (1S) LiPo battery has a nominal voltage of 3.7V, a fully charged voltage of 4.2V, and the lowest discharge voltage of 3V before damage occurs.

ii) A five-cell (5S) LiPo battery pack has a nominal voltage of 18.5V, a fully charged voltage of 21V, and the lowest discharge voltage of 15V before damage occurs.
iii) Never charge/discharge a damaged or swelled LiPo battery pack. Immediately follow proper disposal protocols.
iv) Make sure to discharge your battery down to 3.6V-3.8V per cell for safe storage.

f) Storage
i) LiPo battery packs should never be stored at full charge, nor should it be stored completely discharged. For the longest life cycle, LiPo batteries should be stored at room temperature and at 3.6V-3.8V per cell. Most modern computerized chargers have a LiPo storage function that will either charge the batteries up to that voltage, or discharge them down to that voltage, whichever is necessary for safe storage. It is recommended to put all LiPo batteries in storage mode after every run. In addition, LiPo batteries should be stored in a fireproof container (safe bag), protecting the storage space from catching a fire in case of combustion. Different protection cases can be used such as ammo boxes, fireproof safes, and ceramic flower pots. The most common problem that users have with LiPo batteries is a direct result of improper storage. When a LiPo battery sits for a long period of time without the proper storage voltage, it tends to discharge itself. If it drops below 3V per cell, the vast majority of LiPo chargers will not be able to charge it again.

g) LiPo battery storing tips:
i) LiPo battery packs should be kept well out of reach from children.
ii) Do not place LiPo battery packs in pockets or bags where they can short circuit.
iii) Do not store or transport LiPo batteries where they can come into contact with sharp or metallic objects.
iv) Do not store LiPo battery packs in extreme temperatures below 0°C or above 50°C.
v) Always store LiPo batteries in a safe and fire-resistant container away from flammable objects.
vi) Always store LiPo batteries partially charged. When storing batteries for extended periods, store at a half-charged state.
vii) Do not immerse the LiPo battery in water or allow the battery to get wet.

h) Disposal
i) Before disposing of a LiPo battery, discharge it as far down as you safely can. Most computerized LiPo compatible chargers have a discharge feature available. A second option would be to place the LiPo battery pack in a saltwater bath. Ensure that the wires are entirely submerged. The saltwater is very conductive, and it will essentially short out the battery, further discharging it. Leave the battery in a bucket of saltwater for one week. Since LiPo batteries are not hazardous as NiMH and NiCd ones, they

can be disposed in the trash after fully discharged. Alternatively, if you do not feel like going through this process yourself, follow your municipal battery disposal guidelines or contact your local hobby shop to see if they offer a similar service.

ii) Always follow the LiPo battery manufacturer's safety instructions and charging guidelines. These guidelines are there not only for the longevity of the battery pack, but also for your own safety.