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Method of co-culturing mammalian muscle cells and motoneurons

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(54) **METHOD OF CO-CULTURING MAMMALIAN MUSCLE CELLS AND MOTONEURONS**

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(57) **ABSTRACT**

The invention provides a method of co-culturing mammalian muscle cells and mammalian motoneurons. The method comprises preparing one or more carriers coated with a covalently bonded monolayer of trimethoxysilylpropyl diethylenetriamine (DETA); suspending isolated fetal mammalian skeletal muscle cells in serum-free medium according to medium composition 1; suspending isolated fetal mammalian spinal motoneurons in serum-free medium according to medium composition 1; plating the suspended muscle cells onto the one or more carriers at a predetermined density and allowing the muscle cells to attach; plating the suspended motoneurons at a predetermined density onto the one or more carriers and allowing the motoneurons to attach; covering the one or more carriers with a mixture of medium composition 1 and medium composition 2; and incubating the carriers covered in the media mixture.

11 Claims, 4 Drawing Sheets

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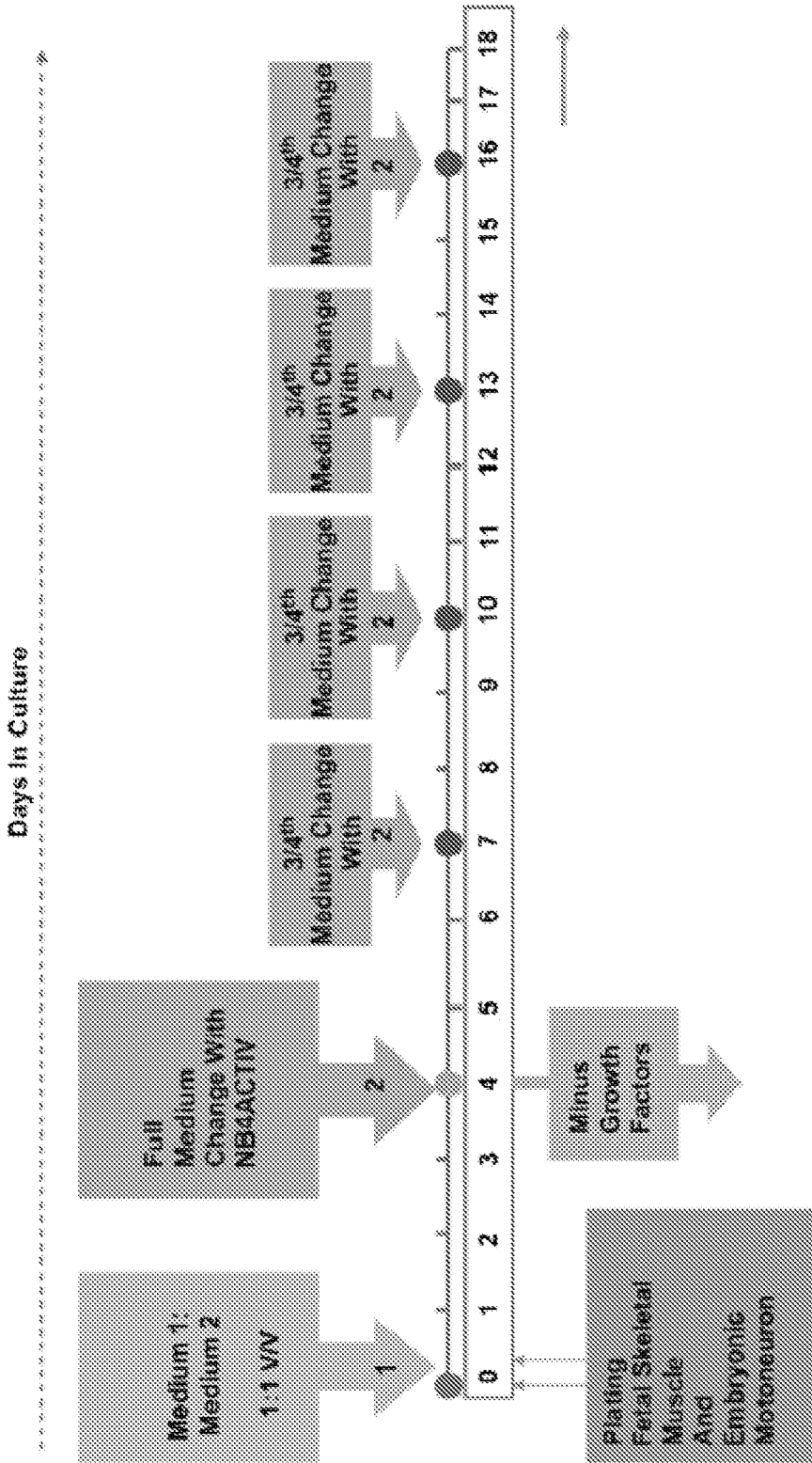


FIG. 1

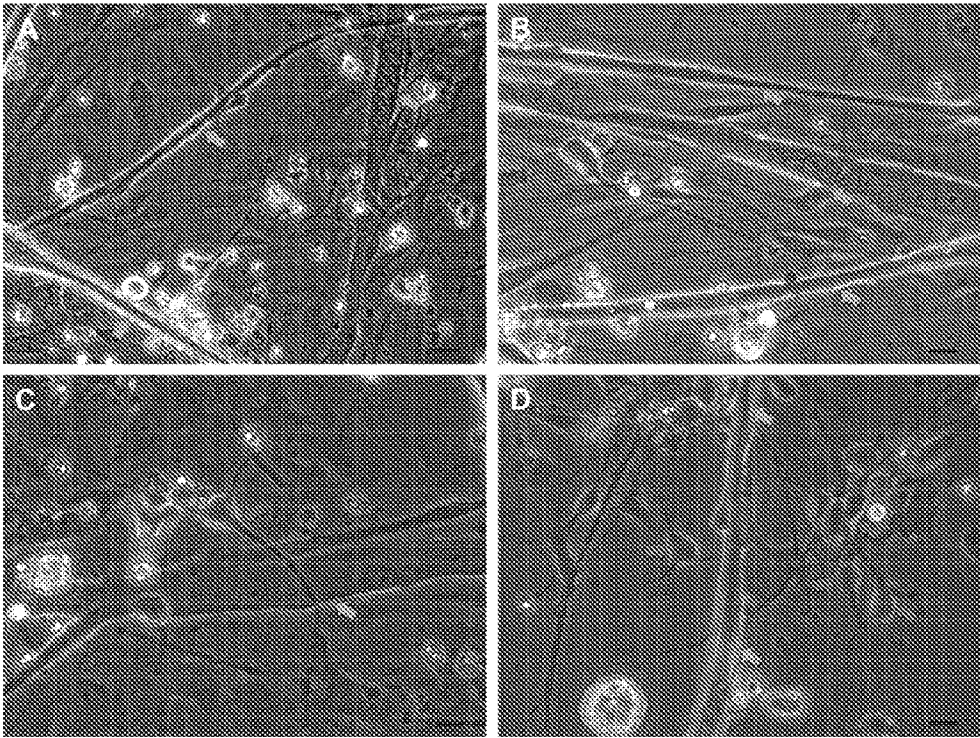


FIG. 2

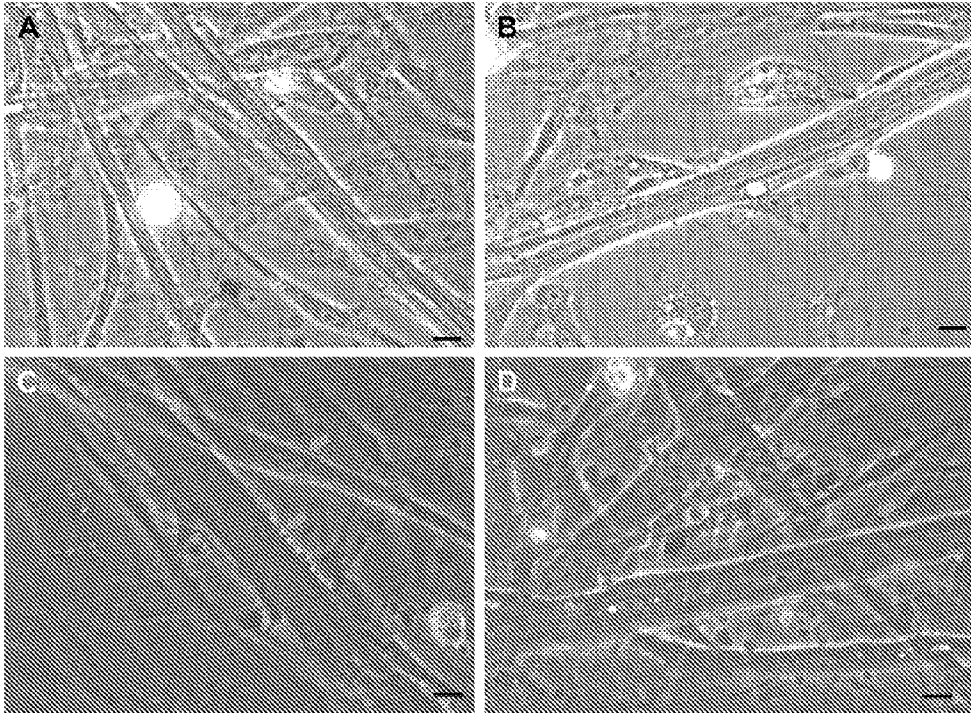


FIG. 3

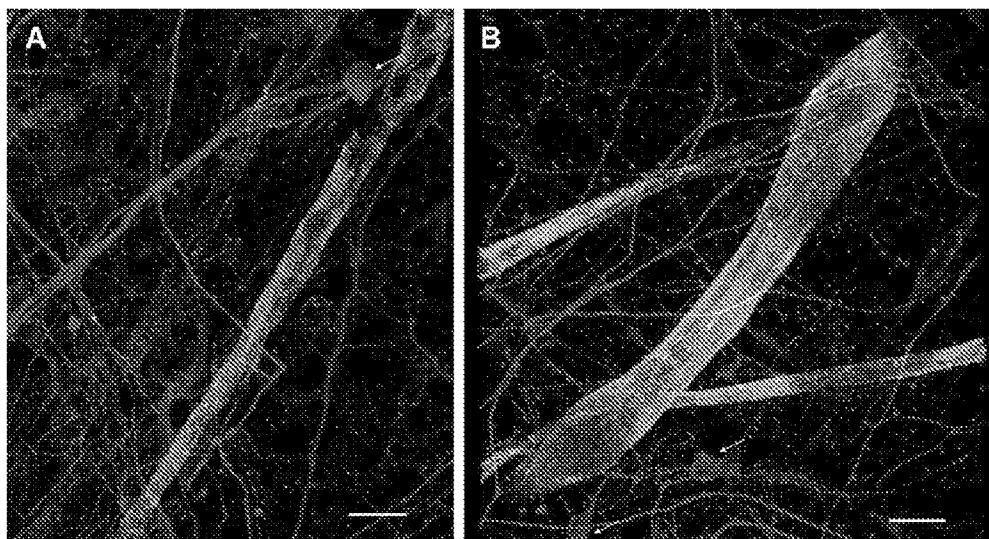


FIG. 4

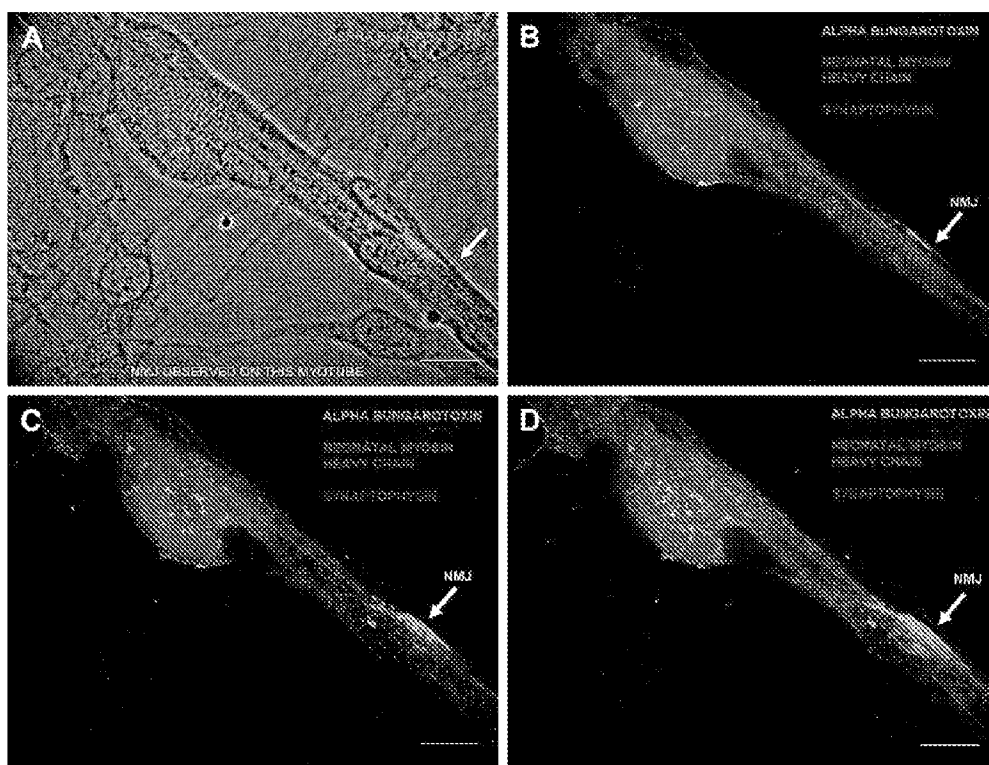


FIG. 5

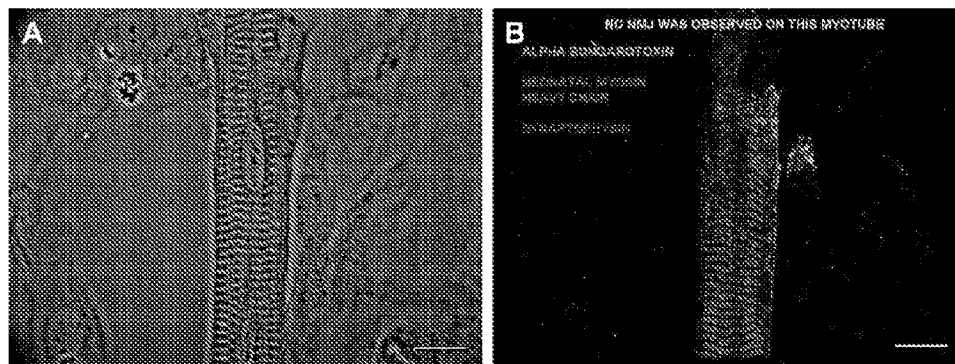


FIG. 6

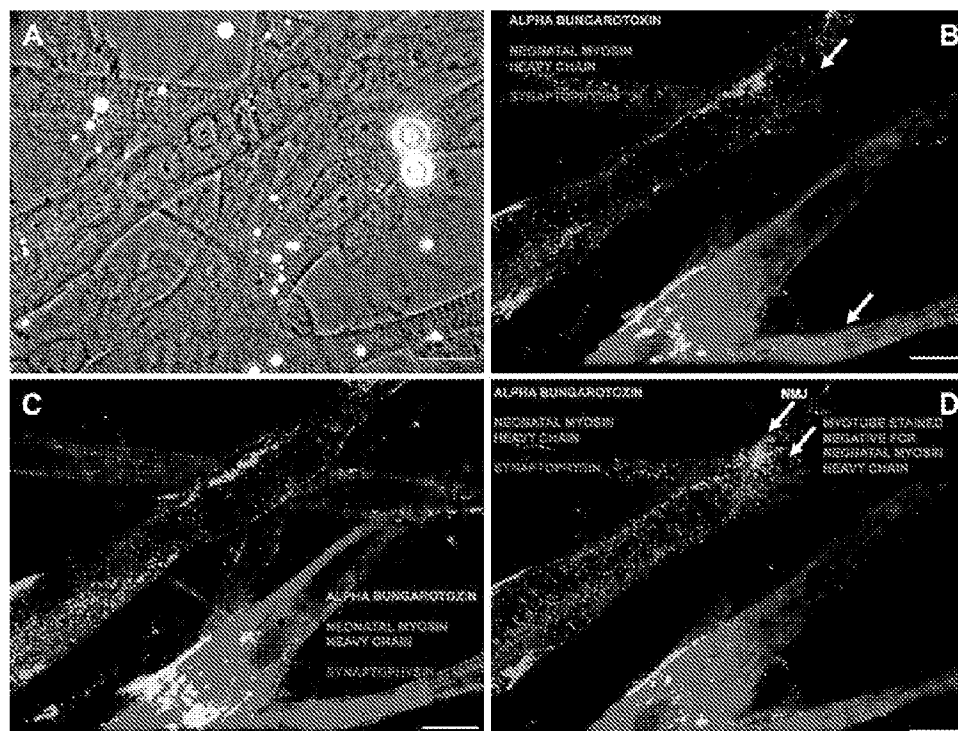


FIG. 7

METHOD OF CO-CULTURING MAMMALIAN MUSCLE CELLS AND MOTONEURONS

RELATED APPLICATION

This application claims priority from provisional application Serial No. 61/171,958 which was filed on 23 Apr. 2009, and which is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under R01 NS050452 awarded by the National Institutes of Health. The government has certain rights in the invention.

FIELD OF THE INVENTION

The present invention relates to the field of neurobiology and, more particularly, to a method of inducing formation of functional neuromuscular junctions in a co-culture of mammalian muscle cells with mammalian motoneurons which remains viable for up to approximately seven weeks.

BACKGROUND OF THE INVENTION

The neuromuscular junction (NMJ), formed between motoneurons and skeletal muscle fibers, is one of the most studied synaptic structures (Witzemann 2006). In a mammalian vertebrate, whenever an action potential is fired by a motoneuron, pre-synaptic vesicles loaded with the neurotransmitter acetylcholine (ACh) are released in the synaptic cleft (Chow et al., 1985). The released ACh diffuses across the synaptic cleft and binds to the post-synaptic terminals in the muscle enriched with receptors for acetylcholine (AChRs). This leads to muscle contraction. In this transmission process the electrical impulses (action potentials) generated by the motoneuron are converted to chemical signals, then the chemical signals are converted into a mechanical signal in the form of muscle contraction. Therefore, not only do NMJs represent an important system for studying synapse formation and maturation, but also for studying how cells interconvert messages between electrical, chemical and mechanical modalities.

In vivo, NMJ formation is a multistep process, requiring the spatial and temporal interaction of growth factors, hormones and cellular structures that results in a pre-synaptic axonal terminal interfaced with a region of the skeletal muscle membrane (postsynaptic) prepatterned with AChRs (Colomar et al., 2004; English 2003). In vitro culture models represent a powerful cell biology tool to study the role of these different growth factors, hormones and cellular structures involved in NMJ formation in a defined, controlled system. Consequently, the development of an in vitro system resulting in NMJ formation would facilitate investigations into the roles of specific factors involved in, and required for, the process to occur efficiently.

However, limited success has been achieved in developing a long-term in vitro system for NMJ formation in the absence of serum containing media and biological substrates. These issues limit the reproducibility of in vitro studies and their translation to tissue engineering applications and high-throughput assay development. For example, the concentration and/or temporal application of medium components could be investigated to determine their influence on NMJ formation, maturation and maintenance. Such a system also benefits from the absence of factors that may be present in

serum that would inhibit these processes. Employing a non-biological growth substrate such as trimethoxysilylpropyl diethylenetriamine (DETA) provides an additional measure of control. DETA is a silane molecule that forms a covalently bonded monolayer on glass coverslips, resulting in a uniform, hydrophilic surface for cell growth. The use of DETA surfaces is advantageous from a tissue engineering perspective because it can be covalently linked to virtually any hydroxylated surface, it is amenable to patterning using standard photolithography (Ravenscroft et al., 1998) and it promotes long-term cell survival because it is non-digestible by matrix metalloproteinases secreted by the cells (Das et al., 2004; Das et al., 2007 (Nat. Protocols)). It is also possible that its structural relationship to the growth factor spermidine, which has recently been shown to prolong cell life (Eisenberg et al., 2009), contribute to its unique ability to enable long-term healthy cell cultures.

Previously, we developed a defined in vitro model facilitating the short-term co-culture of motoneurons and skeletal muscle that resulted in NMJ formation (Das et al., 2007 (Neuroscience)). This model also utilized a biocompatible silane substrate and a serum-free medium formulation. However, further improvements were necessary to enhance the physiological relevance of the NMJ development system. Limitations of the previous model were that it did not support long-term tissue engineering studies and therefore, could not mimic several of the muscle maturation processes observed in vivo by obtaining myotubes that more accurately represent mature extrafusal fibers.

As noted, neuromuscular junction (NMJ) formation, occurring between motoneurons and skeletal muscle, is a complex multistep process involving a variety of signaling molecules and pathways. In vitro motoneuron-muscle co-cultures are powerful tools to study the role of different growth factors, hormones and cellular structures involved in NMJ formation. In this study we have demonstrated a co-culture system that enable sarcomere assembly in the skeletal muscle myotubes as evidenced by A band/I band formation, increased NMJ density and selective myosin heavy chain (MHC) class switching. These results suggest we have discovered a group of biomolecules that act as molecular switches promoting NMJ formation and maturation as well as skeletal muscle fiber maturation to the extrafusal phenotype. This model system will be a powerful tool in basic NMJ research, tissue engineered NMJ systems, bio-hybrid device development for limb prosthesis and in regenerative medicine. It could also be useful in new screening modalities for drug development and toxicology investigations.

SUMMARY OF THE INVENTION

With the foregoing in mind, the present invention advantageously provides a serum-free culture system utilizing defined temporal growth factor application and a non-biological substrate resulted in the formation of robust NMJs. The system resulted in long-term survival of the co-culture and selective expression of neonatal myosin heavy chain, a marker of myotube maturation. NMJ formation was verified by colocalization of dense clusters of acetylcholine receptors visualized using alpha-bungarotoxin and synaptophysin containing vesicles present in motoneuron axonal terminals.

This model will find applications in basic NMJ research and tissue engineering applications such as bio-hybrid device development for limb prosthesis and regenerative medicine as well as for high-throughput drug and toxin screening applications.

The present invention provides a method of co-culturing mammalian muscle cells and mammalian motoneurons. The method yields functional neuromuscular junctions in a culture which is particularly long-lived, up to approximately 7 weeks.

The method includes preparing one or more carriers coated with a covalently bonded monolayer of trimethoxysilylpropyl diethylenetriamine (DETA). The carriers are preferably glass cover slips as used for microscopy applications. The method continues by suspending isolated fetal mammalian skeletal muscle cells in serum-free medium according to medium composition 1, followed by suspending isolated fetal mammalian spinal motoneurons in serum-free medium according to medium composition 1. Next is plating the suspended muscle cells onto the one or more carriers at a predetermined density and allowing the muscle cells to attach and plating the suspended motoneurons at a predetermined density onto the one or more carriers and allowing the motoneurons to attach. The method continues by then covering the one or more carriers with a mixture of medium composition 1 and medium composition 2 and incubating the carriers covered in the media mixture.

It is preferable that in carrying out the presently disclosed method, the practitioner verify DETA monolayer formation by one or more optical parameters, for example, with a contact angle goniometer and by X-ray photoelectron spectroscopy (XPS).

In the method, the mammalian skeletal muscle cells and mammalian spinal motoneurons preferably originate from fetal rats. In this regard, when plating the muscle cells it is preferably done at a density of approximately from 700 to 1000 cells/mm² and the motoneurons are preferably plated at a density of approximately 100 cells/mm². It should be understood that incubating is effected under mammalian physiologic conditions, as is known in the art for mammalian cell tissue culture. Particularly, incubating is best effected at approximately 37° C. in an air atmosphere with about 5% CO₂ and 85% humidity.

In the method, covering comprises a mixture of approximately equal volumes of medium composition 1 and medium composition 2. A complete change of the medium covering the carriers by substituting NbActiv4 medium without growth factors is preferred during the first week of incubation and most preferred on day 4 of incubation. Afterwards, the method calls for changing spent medium as needed with fresh NbActiv4 medium without growth factors. In a preferred embodiment of the method, this periodic changing of the medium may be accomplished every 3 days.

In another embodiment of the presently disclosed method, co-culturing mammalian muscle cells and motoneurons includes allowing fetal muscle cells and fetal spinal motoneurons suspended in a serum-free medium according to composition 1 to adhere to a monolayer of covalently bonded DETA supported on an underlying carrier surface. Following this, the method calls for incubating the adhered muscle cells and motoneurons covered in a mixture of serum-free medium composition 1 and serum-free medium composition 2. Further details of this alternate embodiment are as noted above.

Yet another embodiment or variation of the present invention includes a method of inducing in vitro formation of functional neuromuscular junctions. This embodiment includes depositing a suspension of isolated fetal muscle cells and fetal spinal motoneurons in a mixture of medium compositions 1 and 2 onto a film of DETA supported on a carrier surface, allowing the cells to adhere to the film and culturing the cells under mammalian physiologic conditions. This is followed by changing the medium mixture to medium com-

position 2 without growth factors before seven days of culturing the cells, and exchanging spent medium during culturing for fresh medium composition 2 without growth factors. The method also includes monitoring the cells while culturing for formation of functional neuromuscular junctions between motoneurons and muscle cells.

BRIEF DESCRIPTION OF THE DRAWINGS

Some of the features, advantages, and benefits of the present invention having been stated, others will become apparent as the description proceeds when taken in conjunction with the accompanying drawings, presented for solely for exemplary purposes and not with intent to limit the invention thereto, and in which:

FIG. 1 is a protocol for long-term NMJ formation in a motoneuron and skeletal muscle co-culture, according to an embodiment of the present invention;

FIG. 2 shows phase contrast micrographs of the motoneuron and skeletal muscle co-culture between days 12-15. (A-D); red arrows indicate the distinct morphology of the motoneuron and its processes; green arrows indicate the myotubes; scale bar=25 μm;

FIG. 3 provides phase contrast pictures of the co-cultures between days 25-30; (A, B) the myotubes exhibited characteristic striations; (C, D) myotubes with striations and myotubes without striations; red arrows indicate the motoneuron cell body and the processes; green arrows indicate the myotubes; scale bar for A, B=40 μm; scale bar for C, D=25 μm;

FIG. 4 shows the immunocytochemistry of co-cultures at day 25; (A-B) NF-150 (red) indicates the large motoneurons and their processes (white arrows); the striated myotubes (green) stained for nMHC(N3.36); scale bar=50 μm;

FIG. 5 depicts neuromuscular junction (NMJ) formation between day 30-40; (A) phase picture of the myotube indicating the alpha-bungarotoxin staining in green; (B) triple stain, showing the close proximity of alpha-bungarotoxin (green) and synaptophysin (blue) indicating synapse formation at a specific confocal plane and myotube striations are indicated in red (nMHC); (C-D) NMJ observed at two different planes using confocal microscopy; a much more dense clustering of synaptophysin and alpha-bungarotoxin was observed in these planes;

FIG. 6 shows striated myotube development in the absence of NMJ formation; (A, B) no NMJs were observed on this striated myotube; (A) a phase picture of the myotube; (B) immunostained picture of the same myotube with alpha-bungarotoxin, N3.36 and synaptophysin; scale bar=50 μm; and

FIG. 7 depicts NMJ formation on an N3.36 (-) myotube; (A) phase picture showing the different morphologies of myotubes in the co-culture; (B-D) show that NMJ formation was observed on a myotube that was negative for N3.36; culture stained with alpha-bungarotoxin, N3.36 and synaptophysin; possibly the myotube on which NMJ was formed was immature and had not yet expressed the neonatal myosin heavy chain marker (N3.36).

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention pertains. Although methods and materials similar or equiva-

lent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. Any publications, patent applications, patents, and other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including any definitions, will control. In addition, the materials, methods and examples given are illustrative in nature only and not intended to be limiting. Accordingly, this invention may be embodied in many different forms and should not be construed as limited to the illustrated embodiments set forth herein. Rather, these illustrated embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

Materials and Methods

Surface Modification and Characterization

Glass coverslips (Thomas Scientific 6661F52, 22x22 mm No. 1) were cleaned using an O₂ plasma cleaner (Harrick PDC-32G) for 20 min at 100 mTorr. The DETA (United Chemical Technologies Inc. T2910KG) films were formed by the reaction of the cleaned glass surface with a 0.1% (v/v) mixture of the organosilane in freshly distilled toluene (Fisher T2904). The DETA coated coverslips were then heated to approximately 100° C., rinsed with toluene, reheated to approximately 100° C., and then oven dried (Das et al., 2006). Surfaces were characterized by contact angle measurements using an optical contact angle goniometer (KSV Instruments, Cam 200) and by X-ray photoelectron spectroscopy (XPS) (Kratos Axis 165). XPS survey scans, as well as high-resolution N1s and C1s scans utilizing monochromatic Al K α excitation were obtained (Das et al., 2006).

Skeletal Muscle Culture in Serum-Free Medium

Skeletal muscle was dissected from the thighs of the hind limbs of fetal rat (17e18 days old). Briefly, rats were anaesthetized and killed by inhalation of an excess of CO₂. This procedure was in agreement with the Animal Research Council of University of Central Florida, which adheres to IACUC

policies. The tissue was collected in a sterile 15 mL centrifuge tube containing 1 mL phosphate-buffered saline (calcium- and magnesium-free) (Gibco 14200075). The tissue was enzymatically dissociated using 2 mL of 0.05% of trypsin-EDTA (Gibco 25300054) solution for 30 min in a 37° C. water bath at 50 rpm. After 30 min the trypsin solution was removed and 4 mL Hibernate E/10% fetal bovine serum (Gibco 16000044) was added to terminate the trypsin reaction. The tissue was then mechanically triturated with the supernatant being transferred to a 15 mL centrifuge tube. The same process was repeated two times by adding 2 mL of L15/10% FBS each time. The 6 mL cell suspension obtained after mechanical trituration was suspended on a 2 mL, 4% BSA (Sigma A3059) (prepared in L15 medium) cushion and centrifuged at 300 g for 10 min at 4° C. The pellet obtained was washed 5 times with L15 medium then resuspended in 10 mL of L15 and plated in 100 mm uncoated dishes for 30 min. The non-attached cells were removed and then centrifuged on a 4% BSA cushion (Das et al., 2006).

The pellet was resuspended in serum-free medium according to the protocol illustrated in FIG. 1 and plated on the coverslips at a density of 700-1000 cells/mm². The serum-free medium containing different growth factors and hormones was added to the culture dish after 1 h. The final medium was prepared by mixing medium 1 (Table 1) and medium 2 (Table 2) in a 1:1 v/v ratio. FIG. 1 indicates a flowchart of the culture protocol. Tables 1 and 2 list the growth factor and hormone supplement compositions of medium one and medium two. The cells were maintained in a 5% CO₂ incubator (relative humidity 85%). The entire medium was replaced after four days with NbActiv4 medium according to the protocol in FIG. 1 (Brewer et al., 2008). As described in (Brewer et al., 2008), NbActiv4™ (available from BrainBits LLC) comprises all of the ingredients in Neurobasal™, B27™, and Glutamax™. NbActiv™ may also comprise creatine, estrogen, and cholesterol. Thereafter three-fourths of the medium was changed every three days with NbActiv4.

TABLE 1

Composition of Medium 1				
No. Component	Amount	Catalogue #	Source	References
1 Neurobasal A	500 mL	10888	Gibco/Invitrogen	Brewer et al., 1993
2 Antibiotic-Antimycotic	5 mL	15240-062	Gibco/Invitrogen	
3 Glutamax	5 mL	35050-061	Gibco/Invitrogen	
4 B27 Supplement	10 mL	17504-044	Gibco/Invitrogen	Das et al., 2004; Brewer et al., 1993
5 G5 Supplement (100X)	5 mL	17503-012	Gibco/Invitrogen	Alterio et al., 1990; Clegg et al., 1987; Bottenstein 1981, 1988; Bottenstein et al., 1988; Morrow et al., 1990; Gonzalez et al., 1990; Moore et al., 1991; Anderson et al., 1991; Olwin et al., 1992
6 VEGF _{165r Human}	10 µg	P2654	Gibco/Invitrogen	Arsic et al., 2004; Germani et al., 2003; Lee et al., 2003; Lescaudron et al., 1999
7 Acidic FGF	12.5 µg	13241-013	Gibco/Invitrogen	Alterio et al., 1990; Moore et al., 1991; Olwin et al., 1992; Motamed et al., 2003; Dusterhoft et al., 1999; Fu et al., 1995; Smith et al., 1994; Oliver et al., 1992; Dell'Era et al., 2003
8 Heparin Sulphate	50 µg	D9809	Sigma	Alterio et al., 1990; Moore et al., 1991; Olwin et al., 1992; Motamed et al., 2003; Dusterhoft et al., 1999; Fu et al., 1995; Smith et al., 1994; Oliver et al., 1992; Dell'Era et al., 2003
9 LIF	10 µg	L5158	Sigma	Husmann et al., 1996; Kurek et al., 1996; Megeny et al., 1996; Vakakis et al., 1995; Martinou et al., 1992; Sun et al., 2007; Malm et al., 2004; Zorzano et al., 2003; Sakuma et al., 2000
10 Vitronectin (Rat Plasma)	50 µg	V0132	Sigma	Biesecker 1990; Gullberg et al., 1995
11 CNTF	20 µg	CRC 401B	Cell Sciences	Wang et al., 2008; Chen et al., 2003, 2005; Cannon 1998; Marques et al., 1997
12 NT 3	10 µg	CRN 500B	Cell Sciences	Oakley et al., 1997

TABLE 1-continued

Composition of Medium 1				
No. Component	Amount	Catalogue #	Source	References
13 NT 4	10 µg	CRN 501B	Cell Sciences	Carrasco et al., 2003; Simon et al., 2003
14 GDNF	10 µg	CRG 400B	Cell Sciences	Choi-Lundberg et al., 1995; Lin et al., 1993; Yang et al., 2004; Golden et al., 1999; Henderson et al., 1994
15 BDNF	10 µg	CRB 600B	Cell Sciences	Simon et al., 2003; Heinrich 2003; Mousavi et al., 2004
16 CT-1	10 µg	CRC 700B	Cell Sciences	Chen et al., 2004; Bordet et al. 2001; Dolcet et al., 2001; Lesbordes et al., 2002; Nishikawa et al., 2005; Mitsuimoto et al., 2001; Oppenheim et al., 2001; Peroulakis et al., 2000; Sheng et al., 1996

TABLE 2

Composition of Medium 2				
No. Component(s)	Amount	Catalogue	Source	References
1 Neurobasal A	500 mL	10888	Invitrogen/Gibco	Brewer et al., 1993
2 Glutamax	5 mL	35050-061	Invitrogen/Gibco	
3 Antibiotic-Antimycotic	5 mL	15240-062	Invitrogen/Gibco	
4 B27 Supplement	10 mL	17504-044	Invitrogen/Gibco	Das et al., 2004; Brewer et al., 1993
5 Cholesterol (250X)	5 mL	12531	Invitrogen/Gibco	Jaworska-Wilczynska et al., 2002
6 TNF-alpha, human	10 µg	T6674	Sigma-Aldrich	Caratsch et al., 1994; Al-Shanti et al., 2008; Miller et al., 1988
7 PDGF BB	50 µg	P4056	Sigma-Aldrich	Husmann et al., 1996; Jin et al., 1991; Kudla et al., 1995; Quinn et al., 1990; Yablonka-Reuveni et al., 1995
8 Vasoactive intestinal peptide (VIP)	250 µg	V6130	Sigma-Aldrich	Gold 1982
9 Insulin-like growth factor 1	25 µg	12656	Sigma-Aldrich	Malm et al., 2004; Zorzano et al., 2003; Al-Shanti et al., 2008
10 NAP	1 mg	61170	AnaSpec. Inc.	Gozes et al., 2004; Aracil et al., 2004
11 Recombinant Apolipoprotein E2	50 µg	P2002	Panvera	Robertson et al., 2000
12 Laminin, mouse purified	2 mg	08-125	Millipore	Langen et al., 2003; Foster et al., 1987; Hantai et al., 1991; Kuhl et al., 1986; Lyles et al., 1992; Song et al., 1992; Swadison et al., 1992
13 Beta amyloid (1-40)	1 mg	AG966	Millipore	Wang et al., 2005; Yang et al., 2007; Akaaboune et al., 2000
14 Human Tenascin-C protein	100 µg	CC065	Millipore	Hall et al., 2000
15 rr-Sonic hedgehog, Shh N-terminal	50 µg	1314-SH	R&D Systems	Fan et al., 1994; Munsterberg et al., 1995; Nelson et al., 1996; Cossu et al., 1996; Currie et al., 1996; Norris et al., 2000; Brand-Saberli et al., 2005; Elia et al., 2007; Pagan et al., 1996; Bren-Mattison et al., 2002; Mayes et al., 2007; Koleva et al., 2005
16 rr (Agrin C terminal)	50 µg	550-AG-100	R&D Systems	Bandi et al., 2008; Sanes 1997

Rat Embryonic Motoneuron Isolation and Co-Culture

Rat spinal motoneurons were purified from ventral cords of embryonic day 14 (E14) embryos. Briefly, rats were anaesthetized and killed by inhalation of an excess of CO₂. This procedure was in agreement with the Animal Research Council of University of Central Florida, which adheres to IACUC policies. Ventral spinal cord cells from the embryo were collected in cold Hibernate E/GlutaMAX/antibiotic-antimycotic/B27. The cells were dissociated with 0.05% trypsin-EDTA (Invitrogen) treatment for 15 min. The dissociated cells were layered over a 4 mL step gradient Optiprep diluted 0.505:0.495 (v/v) with Hibernate E/GlutaMAX/antibiotic-antimycotic/B27 and then made to 15%, 20%, 25% and 35% (v/v) in Hibernate E/GlutaMAX/antibiotic-anti-mycotic/B27 followed by centrifugation for 15 min, using 200 g at 4° C. After centrifugation, four bands of cells were obtained. The motoneurons with large somas constituted the uppermost band. These cells present in the uppermost band were collected in fresh Hibernate E/GlutaMAX/antibiotic-anti-mycotic/B27 and centrifuged for 5 min at 200 g and 4° C. The

pelleted motoneurons were resuspended in plating medium then plated on top of muscle cells at a density of 100 cells/mm². Motoneuron plating was performed 30 min after plating of the muscle cells.

Immunocytochemistry

Neonatal Myosin Heavy Chain (Neonatal MHC)

Coverslips were rinsed with PBS, fixed in 20° C. methanol for 5-7 min, washed in PBS, incubated in PBS supplemented with 1% BSA and 0.05% saponin (permeabilization solution), and blocked for 30 min in a permeabilization solution+ 10% goat serum (blocking solution). Cells were incubated overnight with primary antibody against neonatal MHC (N3.36, IgG, Developmental Studies Hybridoma Bank) diluted (1:5) in the blocking solution. Cells were washed with PBS and incubated with AlexaFluor secondary antibody (Invitrogen) (diluted in PBS) for 2 h. The secondary antibody solution was removed and the cells were rinsed using PBS. The coverslips were dried and mounted on glass slides using VectaShield+DAPI mounting medium (Vector Laboratories H-1200) and viewed on a confocal microscope (UltraVIEW LCI, PerkinElmer).

Double Staining with Neurofilament 150 and Neonatal Myosin Heavy Chain

Co-cultures were processed for immunocytochemistry as described above. Next, cells were incubated overnight at 4° C. with rabbit anti-neurofilament M polyclonal antibody, 150 kD, (Chemicon, AB1981, diluted 1:2000) and neonatal MHC (N3.36, IgG, Developmental Studies Hybridoma Bank diluted 1:5). After overnight incubation, the coverslips were rinsed three times with PBS and then incubated with the AlexaFluor secondary antibodies (Invitrogen) for 2 h. After rinsing three times in PBS, the coverslips were mounted with Vectashield+DAPI mounting medium onto glass slides. The coverslips were visualized and images collected using a confocal microscope (UltraVIEW LCI, PerkinElmer). Controls without primary antibody were negative.

AChR+Synaptophysin Co-Staining

AChRs were labeled as described previously by incubating cultures with 5×10^{-8} M of α -bungarotoxin, Alexa Fluor® 488 conjugate (Molecular Probes, B-13422) for 1.5 h at 37° C. before observation (Das et al., 2007 (Neuroscience)). Labeled cultures were fixed with glacial acetic acid and ethanol, washed with PBS, dried, mounted and examined by confocal microscopy. The coverslips which were used for double staining with AChR+synaptophysin for locating the NMJs were processed further. After 1.5 h of α -bungarotoxin labeling of the AChR receptors, the coverslips were fixed, blocked, permeabilized and incubated overnight with synaptophysin antibody (MAB368, diluted 1:1000; Millipore/Chemicon), the pre-synaptic marker present in motoneuron axonal terminals.

Data Analysis
Statistics were calculated using the following procedure. One coverslip was randomly selected from each experiment (typically, there are six coverslips per experiment). 25 non-overlapping fields of view were used to characterize each coverslip. At the magnification used, 25 fields covers over 40% of the surface area of the coverslip.

Results

DETA Surface Modification and Characterization

Static contact angle and XPS analysis were used for the validation of the surface modifications and for monitoring the quality of the surfaces. Stable contact angles ($40.64^\circ \pm 2.9/\text{mean} \pm \text{SD}$) throughout the study indicated high reproducibility and quality of the DETA surfaces and these characteristics were similar to previously published results (Das et al., 2004; Das et al., 2007 (Nat. Protocols); Das et al., 2007 (Neuroscience); Das et al., 2006; Das et al., 2003). Based on the ratio of the N is (401 and 399 eV) and the Si $2p_{3/2}$ peaks, XPS measurements indicated that a reaction-site limited monolayer of DETA was formed on the coverslips (Stenger et al., 1992).

Temporal Growth Factor Application

The formation of the maximal number of neuromuscular junctions was observed using the temporal growth factor application technique described in FIG. 1. Upon plating of the motoneurons and skeletal muscle, the cells were treated with medium containing factors that promoted both growth and survival as well as enhancement of NMJ formation (Table 1, Table 2). After 3 days in culture, the entire medium was removed and switched to a minimal formulation, NbActiv4, which facilitated both long-term survival and further development of the NMJs (FIG. 1). Further, three-fourths of the NbActiv4 medium per well was removed and replaced with an equal volume of fresh NbActiv4 medium. When compared to the continuous application of growth factors, the timed application resulted in cultures that lasted for up to 7 weeks as opposed to 10-12 days.

Culture Morphology of Motoneuron and Skeletal Muscle Myotube Interactions

Phase contrast microscopy was used to visualize motoneuron axons appearing to interact with skeletal muscle myotubes between days 12-15 (FIG. 2, A-D). Some of the axonal processes appear to branch and terminate on the myotubes. Furthermore, many of the myotubes exhibited characteristic striation patterns observed after sarcomere formation when the fibers reached approximately 25-30 days in culture (FIG. 3, A-D). Quantification of the appearance of striations after this time indicated that the co-cultures contained about twice the number of myotubes showing striations.

Immunocytochemical Characterization of Motoneuron and Skeletal Muscle Co-Culture

The characteristic protein expression patterns of the motoneurons and myotubes in co-culture were evaluated at day 25. Immunocytochemistry was used to visualize the neurofilament protein expression in the motoneurons and neonatal myosin heavy chain (MHC) expression for the myotubes (FIG. 4, A-B). Motoneuron processes were clearly indicated interacting with the skeletal muscle myotubes. A band/I band formation was more visible in the myotubes after staining with the neonatal myosin heavy chain antibody. The immunocytochemical analysis supported the morphological analysis, which had indicated the presence of striations in double the number of myotubes as observed with the muscle only controls.

Neuromuscular Junction Formation

In order to determine neuromuscular junction formation using this novel medium formulation, the clustering of AChRs using alpha-bungarotoxin and their colocalization with synaptophysin vesicles was analyzed immunocytochemically. The colocalization of these two synaptic markers indicated the proximity of pre-synaptic and post-synaptic structures and was a positive indication of NMJ formation. This technique was used to identify the colocalization of synaptophysin vesicles with the AChR clusters (FIG. 5, A-D). The axon+myotube interactions that did not result in the colocalization of pre-synaptic and post-synaptic structures were also identified (FIG. 6, A-B). The observation of the negative result defines the difference between colocalization and non-colocalization and emphasizes the positive result observed in this system. FIG. 7 illustrates NMJ formation between a myotube in culture that did not stain for neonatal myosin heavy chain and a motoneuron.

Discussion

This work documents the substantial improvement of an in vitro model system for NMJ formation. Specifically, we observed enhanced survivability of the culture resulting in our ability to conduct long-term studies on the motoneuron-skeletal muscle cocultures. This increased survivability resulted in maturation of the skeletal muscle myotubes and a significant improvement in the number of NMJs formed in culture.

Previously, we developed the first defined culture model to coculture embryonic motoneuron and fetal skeletal muscle, however this model was not suitable for long-term tissue engineering studies and the myotubes in the culture only expressed an early muscle marker, i.e. fetal myosin heavy chain and none of the myotubes exhibited characteristic striations. In this study, significant improvement over our previous motoneuron-skeletal muscle co-culture model system was documented. This new culture model supported long-term co-culture of both motoneuron and muscle, resulted in a more adult-like morphology of the muscle and a higher density of neuromuscular junctions (NMJ). Our findings were supported by morphological and immunocytochemical data.

We developed this serum-free medium, supplemented with growth factors that supported the survival, proliferation and fusion of fetal rat myoblasts into contractile myotubes, in a semi-empirical fashion. The rationale for selecting the growth factors was based on the distribution of their cognate receptors in the developing myotubes in rat fetus (Arnold et al., 1998; Brand-Saberi et al., 2005; Olson et al., 1992). Tables 1 and 2 reference the literature where these individual growth factors, hormones and neurotransmitters were observed to support muscle and neuromuscular junction development. The composition in Table 1 is the formulation used for a previously published medium utilized for motoneuron-muscle co-culture and adult spinal cord neuron culture (Das et al., 2007 (Neuroscience); Das et al., 2008 (Exp. Neurology); Das et al., 2005; Das et al., 2007 (Biomaterials)). Table 2 lists the twelve additional factors identified in muscle development and neuromuscular junction formation that enabled the increased survivability of the system. Further addition of the factors in Table 2 promoted formation of characteristic striation in the muscle in the culture. The use of NbActiv4 for the maintenance of the cells significantly improved the survival of the skeletal muscle derived myotubes despite the fact that the original purpose of the development of NbActiv4 was for the long-term maintenance and synaptic connectivity of fetal hippocampal neurons in vitro (Brewer et al., 2008).

In our previous co-culture model, we did not observe the expression of neonatal MHC proteins in the myotubes. Interestingly, when this same medium and protocol was used to culture pure skeletal muscle we observed certain striking differences. The pure muscle culture survived longer, exhibited characteristic striations, but only a very small percentage of myotubes expressed N3.36 (Das et al., 2009 (Biomaterials)). To the best of our understanding, the N3.36 expression in skeletal muscle in culture is influenced by the motoneurons either physically or by certain trophic factors secreted in the presence of this modified medium and NbActiv4. This observation needs further studies in order to dissect the molecular pathways regulating N3.36 expression in pure skeletal muscle culture and in skeletal muscle-motoneuron co-culture. Also, the potential regulation of MHC class switching independent of neuronal innervation/denervation represents an interesting topic for further study. This system would have applications in developing therapies for muscle-nerve diseases such as ALS, spinal muscular atrophy, spinal cord injury and myasthenia gravis.

CONCLUSIONS

The development of robust NMJ formation, long-term survival of motoneuron \bar{b} skeletal muscle co-cultures and selective MHC class switching is documented in this research. This improved system supports the goal of creating a physiologically relevant tissue engineered motoneuron \bar{b} skeletal muscle construct and puts within reach the goal of developing functional bio-hybrid devices to analyze NMJ activity. This defined model can also be used to map the developmental pathways regulating NMJ formation and MHC class switching. Furthermore, we believe this serum free culture system will be a powerful tool in developing advanced strategies for regenerative medicine in ALS, stretch reflex arc development and integrating motoneuron+skeletal muscle with bio-hybrid prosthetic devices. Due to the use of a serum-free defined culture system this also has applications for new high-throughput screening systems for use in drug discovery research and toxicology investigations.

Accordingly, in the drawings and specification there have been disclosed typical preferred embodiments of the invention and although specific terms may have been employed, the terms are used in a descriptive sense only and not for purposes of limitation. The invention has been described in considerable detail with specific reference to these illustrated embodiments. It will be apparent, however, that various modifications and changes can be made within the spirit and scope of the invention as described in the foregoing specification and as defined in the appended claims.

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- That which is claimed:
1. A method of co-culturing mammalian muscle cells and motoneurons, the method comprising:
 - suspending fetal muscle cells and fetal spinal motoneurons in a serum-free medium according to composition 1 of Table 1;
 - placing the suspended fetal muscle cells and fetal spinal motoneurons onto a monolayer of covalently bonded trimethoxysilylpropyl-diethylenetriamine supported on an underlying carrier surface; covering the carrier comprising muscle cells and motoneurons in a mixture of serum-free medium composition 1 of Table 1 and serum-free medium composition 2 of Table 2; and
 - incubating the covered carrier comprising muscle cells and motoneurons.
 2. The method of claim 1, wherein the fetal muscle cells and motoneurons originate from fetal rats.
 3. The method of claim 1, wherein the underlying carrier surface comprises a glass cover slip.
 4. The method of claim 1, wherein incubating is under mammalian physiological conditions.
 5. The method of claim 1, wherein incubating is at approximately 37° C. in an atmosphere of air with about 5% CO₂ and 85% humidity.
 6. The method of claim 1, wherein the mixture of medium composition 1 of Table 1 and medium composition 2 of Table 2 comprises approximately equal volumes of each composition.
 7. The method of claim 1, further comprising changing the covering medium to a Neurobasal/B27/Glutamax-based medium comprising creatine, estrogen, and cholesterol without growth factors as incubating proceeds.
 8. The method of claim 1, further comprising changing the covering medium to a Neurobasal/B27/Glutamax-based medium comprising creatine, estrogen, and cholesterol without growth factors during the first week of incubation.
 9. The method of claim 8, further comprising periodically changing the covering medium after the first week with fresh Neurobasal/B27/Glutamax-based medium comprising creatine, estrogen, and cholesterol without growth factors.
 10. The method of claim 1, further comprising, during the incubating, monitoring the carrier for formation of myotubes by the incubated muscle cells.
 11. The method of claim 1, further comprising, during the incubating, monitoring the carrier for formation of neuromuscular junctions between the incubated motoneurons and muscle cells.